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THIXOCASTING STEEL PARTS

September 1978

by M. C. Flemings, John F. Boylan, Richard L. Bye

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Materials Science and Engineering
Cambridge, Massachusetts 02139

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This report describes the Thixocasting process as applied to the die casting of small, AISI 4340 parts. 2,200 shots of semi-solid AISI 4340 were cast in an industrial die casting machine to investigate the feasibility of the Thixocast process for this low alloy steel. The Thixocastings produced demonstrate good quality with radiographic examination showing low porosity levels. The rheological behavior of Rheocast AISI 4340 is qualitatively similar to that of other alloys previously over

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ABSTRACT

studied. Thus, the viscosity of a Rheocast AISI 4340 slurry increases with increasing fraction solid, and at a given fraction solid, it increases with increasing solidification rate and decreasing shear rate. The effective primary solid particle size increases with increasing fraction solid, and over solidification rates of between 0.50 min^{-1} and 1.00 min^{-1}, the effective primary solid particle size at a given fraction solid decreases with increasing shear rate up to a shear rate of 900 sec^{-1}. Cu-1% Cr-19% Zr die inserts used to Thixocast 4340 low alloy steel has been demonstrated to be far superior to standard tool steel die materials (H-13 and H-21) for ferrous alloy machine casting. Die life has been estimated at 10,000 shots and no shot sleeve warpage was encountered when employing the semi-solid charge material. An economic analysis using a specific small AISI 4340 part has been performed to determine the commercial feasibility of the Thixocast process. Assuming a die life of 10,000 shots between reworkings, a manufacturing cost of 15.38¢ per part is calculated for electro-discharge machining (EDM). With investment casting used to shape die cavity inserts, the manufacturing cost is 9.48¢ per part for a similar die life of 10,000 shots. These costs compare favorably with alternate forming processes. For example, the approximate cost of manufacturing the specified part by investment casting would be 16¢ per part.

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ABSTRACT

This is the final report describing research conducted at the Massachusetts Institute of Technology on "Thixocasting of Steel Parts". It covers a one-year contract period, beginning 1 April, 1977, and represents a follow-up concluding study to the four-year ARPA-sponsored research program conducted at M.I.T. on "Machine Casting of Ferrous Alloys".

The Thixocasting process was applied to the die casting of small, AISI 4340 parts. The process comprised: (1) the continuous production of a semi-solid metal slurry by vigorous agitation during initial solidification, (2) complete solidification of the slurry in ingot form, (3) reheating of the ingot to the casting temperature within the liquid-solid region, and (4) casting of the semi-solid ingot in a conventional cold-chamber die casting machine (in this case, employing copper dies (Cu-1% Cr-19% Zr) operating at 50°C.).

Approximately 2000 pounds of 10-ounce AISI 4340 ingots were produced in a high temperature continuous Rheocaster. Design, control method, and operation of

the Rheocaster is described in detail. The rheological behavior of Rheocast AISI 4340 is qualitatively similar to that of other alloys previously studied (e.g., tin-lead, copper, aluminum, and other ferrous alloys). The viscosity of a Rheocast AISI 4340 slurry increases with increasing fraction solid and decreasing shear rate.

2,200 shots of semi-solid AISI 4340 were cast in an industrial die casting machine to investigate the feasibility of the Thixocast process for low alloy steel. The operating procedure and system components are described in detail. Thixocastings produced demonstrate good quality. Primary solid particles were uniformly distributed in a rapidly solidified matrix. The average volume fraction of primary solid particles in the charge material was 0.41. Thixocast 4340 low alloy steel experienced very rapid cooling rates during solidification ($>10^4$°C/sec) when machine cast in Cu-Cr-Zr dies operating at 50°C. Radiographic examination of the Thixocast parts showed low porosity levels.

The Cu-Cr-Zr alloy has been demonstrated to be far superior to standard tool steel die materials (H-13 and H-21) for ferrous alloy machine casting. Based on the condition of the die cavity insert set after 2,200 shots, die life has been estimated at 10,000 shots. No shot sleeve warpage was encountered when employing a semi-solid charge material.

An economic analysis using a specific small AISI 4340 part has been performed to determine the commercial feasibility of the Thixocast process. Using electro-discharge machining (EDM) for die cavity preparation and assuming a die life of 10,000 shots between reworkings, a manufacturing cost of 15.38¢ per part is calculated. Significant economic advantage can be realized by the use of investment casting to shape die cavity inserts, provided a similar die life of 10,000 shots is realized. A manufacturing cost of 9.48¢ per part is calculated.

These costs compared favorably with alternate forming processes. For example, the approximate cost of manufacturing the specified part by investment casting would be 16¢ per part.

I. INTRODUCTION

In January, 1973, a joint university-industry research program was undertaken to develop an economical method of machine casting ferrous alloys. The portion of this program conducted at M.I.T. dealt primarily with Rheocast and Thixocast development. In Rheocasting, a semi-solid slurry of a metal alloy is produced by vigorous agitation of a solidifying melt. This highly fluid slurry, having a consistency of a heavy machine oil, is then cast directly to shape. In Thixocasting, shown schematically in Figure 1, fully solidified ingots of Rheocast metal are reheated to the liquid-solid region and cast. Due to the thixotropic nature of Rheocast slurries, the reheated charges retain their shape and can be handled as soft solids during transfer to the die casting machine. The high shear rates experienced by the metal during casting reduces the slurry viscosity to a level at which it flows smoothly into the die cavity.

Work at M.I.T. performed under the "Machine Casting of Ferrous Alloys" program has demonstrated the technical feasibility of the Thixocast process for machine casting small parts. Development efforts have been conducted with tin-lead, copper, aluminum, and several stainless steel alloys[1-6]. Die life studies performed under that program with various die materials have shown that the Thixocast process utilizing surface quenched copper base Elbrodur RS dies extends die life beyond that possible with liquid ferrous alloys die cast with conventional mold materials. Figure 2, taken from this earlier work[6], and showing the 500th castings produced in H-13 and H-21 tool die steels,

Cu-0.8% Cr, and Elbrodur RS dies, demonstrates that copper dies have a longer life than do conventional steel dies.

During this contract year, the basic Thixocasting system was adapted for pilot plant production of low alloy steel components to demonstrate the technical and economic feasibility of producing large quantities of these parts by the Thixocasting process. The specific objectives of the work presented herein are:

1. to adapt the Rheocaster and Thixocasting system for use with AISI 4340 low alloy steel,

2. to study the relationships between process variables and the rheological behavior of AISI 4340 slurries,

3. to investigate the effects of Thixocasting AISI 4340 on machine component lives, especially die life,

4. to evaluate the quality of AISI 4340 parts produced by the Thixocast process, and

5. to evaluate the economic feasibility of the Thixocast process for large volume production of low alloy steel parts.

II. RHEOCASTING

The major aim of this program has been to determine the feasibility of producing ferrous parts by the Thixocasting process. In line with this aim, approximately 2000 pounds of Rheocast AISI 4340 have been produced for subsequent use in the Thixocast pilot plant studies.

Using the standard Rheocaster, data were collected during production runs and separate tests conducted to determine the reliability of the method used to control the Rheocaster and to examine the relationships between the physical characteristics of the 4340 slurries and the process conditions under which they were made. These relationships were then compared to those found in earlier work[7-10] using tin-lead alloys.

A. System Design and Operation

1. The High Temperature Continuous Rheocaster

A picture of the high temperature continuous Rheocaster and its support equipment is shown in Figure 3. A schematic drawing of the Rheocaster is shown in Figure 4.

Only minor modifications in the continuous Rheocasting system developed at M.I.T. were necessary to adapt it for Rheocast AISI 4340 production. Improved shielding of the melt and the exit area has been accomplished by the increased use of argon-4% hydrogen. This has resulted in cleaner ingots that are free of blow holes and has reduced slag attack on furnace parts.

The ingot-making procedure has also been changed for Rheocast AISI 4340 production. Exiting Rheocast metal is now collected in Fiberfrax lined molds which are handled individually on a rotating turntable rather than being packed into canisters as were the stainless steel molds employed previously. The ingots are 1-1/4 in. diameter and 1-3/4 in. long and weigh approximately 10 ounces. After the molds have filled, the top of the ingot is tamped so that both ends of the ingot are flat. These ingots can be Thixocast directly, eliminating the time and material waste involved in cutting larger ingots into separate charges. The graphite molds last longer than do the stainless steel molds used previously and are more easily prepared for re-use. In addition, these shot-sized ingots have been found to reheat more uniformly than sectioned ingots.

During continuous production of Rheocast AISI 4340, 9/16" diameter rod stock is continuously melted in the upper chamber of the Rheocaster. At the same time, metal flowing into the mixing chamber is cooled and vigorously agitated by the turning rotor to produce the characteristic Rheocast structure. The semi-solid slurry is extracted from the bottom of the mixing chamber at a controlled volume fraction of solid.

The main body of the Rheocaster is a slip cast, 1/2" thick crucible made from Vesuvius #235 (58% Al_2O_3, 26% C, 12% SiO_2). The upper chamber, which is the melting and holding chamber, is 5-3/8" in diameter and 7-1/2" high and holds approximately 40 pounds of molten steel. The top chamber is inductively heated by a 30 KW, 4.2 KHz Inductotherm motor generator unit. The melt is insulated and

protected from the atmosphere by a layer of fire-brick and two layers of Fiberfrax blanket. Argon-4% hydrogen is introduced to the holding chamber through a stainless steel tube to further protect the melt. The gas flow is regulated so that a flame burns at the openings in the Fiberfrax cover (around the rotor and the hole through which the feed stock is introduced), indicating that oxygen has been excluded from the melt. The melt temperature is monitored by a Pt-Pt 10% Rh thermocouple located in an alumina sheath cemented to the crucible wall.

The mixing chamber consists of a 6" long alumina combustion tube (1-1/4" ID x 1-1/2" OD,with a 1/4" diameter exit hole) cemented inside the Vesuvius crucible. An induction coil, powered by a 20 KW, 10 KHz Radio Frequency Company solid state inverter, surrounds the mixing chamber. With the power turned down, this coil acts as a cooling coil for the mixing chamber. A recrystallized alumina sleeve and 100 mesh alumina powder separate the coil from the crucible.

In the lower chamber of the Rheocaster, the exit chamber, the nozzle end of the alumina combustion tube is supported by a specially machined graphite piece and a ceramic disk. Argon-4% hydrogen flows through the gap between two concentric alumina tubes cemented inside the graphite piece and into the exit chamber to shield the exiting Rheocast metal and prevent slagging up of the exit port. A quartz tube is used to extend the gas shield to the top of the ingot molds. The exit chamber is heated to prevent slurry from freezing in the exit port by an induction coil powered by a 10 KW, 190 to 610 KHz Lepel induction

unit. Temperature at the exit port is monitored by a Pt-Pt 10% Rh thermocouple cemented to the outside of the crucible wall.

The mixing rotor is an 18-3/4" long hollow alumina tube with an outside diameter of 1-1/8". The lower six inches of the rotor has a square cross section (1-1/8" from corner to corner) to promote agitation and avoid flow instabilities in the mixing chamber. The rotor is driven by a 3/4 h.p. direct current motor capable of turning the rotor at speeds of between 0 and 1200 RPM. The rotation speed is controlled by a Minarik Model MR90 constant speed controller and measured with a tachometer placed on top of the rotor assembly. An ammeter is placed in line with the motor to measure the amperage required to drive the rotor at a given speed. The rotor assembly is designed to allow the rotor to be raised or lowered to control the flow rate of the exiting Rheocast slurry. The rotor can be seated on the bottom of the mixing chamber to completely stop flow.

Three Pt-Pt 10% Rh thermocouples are placed inside the rotor. They monitor the temperature at the bottom and middle of the mixing chamber and in the upper reservoir. A set of rotary contacts has been designed to permit continuous monitoring of the EMF from these rotating thermocouples. The thermocouples are attached to a series of copper slip rings located at the top of the rotor assembly. Electrical contact is made with a set of spring loaded carbon brushes. The output of all thermocouples in the Rheocaster is displayed on a Hewlett-Packard 7100 BM two-channel chart recorder and a Keithley 190 digital voltmeter.

2. Operating Procedure

a. Continuous Production

At the start of a Rheocast production run the rotor is positioned in the mixing chamber with a rotor-exit separation of about 1/8" to allow for thermal expansion. Approximately 20 pounds of feed metal is placed in the top chamber. Argon-4% hydrogen flow is turned on to both the top and exit chambers. Power to all three induction coils is then turned on and adjusted so that a relatively level temperature profile, as indicated by the thermocouples located at the exit, in the mixing chamber, and in the top reservoir, is maintained. Thermal shock is thereby minimized when the metal in the top reservoir melts.

After the initial charge has melted, the rotor is seated at the exit port with the minimum pressure required to prevent metal flow. The power supplies are adjusted to stabilize the melt temperature with a superheat of about 40°C. The rotor is then rotated slowly while additional metal is added to fill the upper chamber.

After the upper chamber is full, the rotation speed of the rotor is adjusted to the desired level and the amperage required to turn the rotor in the liquid metal is recorded as a base level amperage. Power to the middle coil is reduced so that enough heat is extracted from the metal in the mixing chamber to produce the desired solidification rate.

From this point on, the Rheocaster is controlled exclusively by monitoring the amperage required to drive the rotor at constant speed. As the fraction of solid of the Rheocast slurry increases, the viscosity increases,

and the amperage needed to drive the rotor increases. When the desired amount of amperage increase above the base level is reached, the rotor is raised and the metal flow rate is adjusted to stabilize the amperage reading.

Exiting Rheocast metal is teemed into graphite molds lined with a 1/16" layer of Fiberfrax paper. Each ingot weighs approximately 10 ounces. The fill time and amperage reading during that time are recorded for each ingot. The ingots are subsequently weighed and the flow rate for each ingot is calculated from the fill time and the weight. Water-quenched samples of exiting Rheocast metal are collected periodically for subsequent metallographic examination.

The Rheocaster is capable of producing approximately 250 pounds of 50% solid 4340 slurry per hour but the melting rate is limited to about 60 pounds per hour by the size of the available power supply. During production, the metal flow rate is held to between 80 and 100 pounds per hour. At these rates, production can operate on a semi-continuous basis while still allowing for good ingot fill-out.

Furnace life is currently limited to about 15 hours. Failures are not catastrophic and wear of the furnace parts is not a factor in furnace life. Furnaces are generally rejected because of a slight shift of the exit area with respect to the rotor. This shift eventually results in severe rotor vibration and loss of flow rate control. A minor design change to hold the crucible more rigidly would significantly extend furnace life.

b. <u>Static Tests</u>

Static, viscometer-like tests were conducted in the

Rheocaster immediately after continuous production runs were completed. The metal in the mixing chamber was heated until it was completely liquid. The rotor speed was then adjusted to the desired level and the power to the middle coil was turned down. The rotor was seated at the exit port so that no metal flow could occur. As the metal solidified, amperage readings were recorded at the appropriate points on the chart recorder trace of the middle rotor thermocouple output. Amperage and temperature were continuously monitored until the slurry fraction of solid became so high that the motor shut off and the rotor seized. The mixing chamber was then reheated to above the alloy liquidus for another trial. Experiments were run at several rotation speeds and solidification rates.

Cooling and heating curves were also generated without rotor rotation to determine the freezing range of 4340. The liquidus and solidus breaks in the chart recorder trace of the middle rotor thermocouple were noted and found to be consistent for several cooling and heating cycles. The freezing range of 4340 was found to be 73°C. The liquidus break occurred at 1479°C.

B. Determination of Parameters

The three important process variables in Rheocasting are fraction of solid, shear rate, and solidification rate or cooling rate. In this study, the effects of these variables on the primary particle size and the slurry were studied.

1. Fraction of Solid

a. Continuous Production

Fractions of solid from the continuous production runs were determined metallographically from the water-quenched samples taken during the runs. The samples were mounted and then polished in successive steps on wet, rotating silicon carbide papers of 30, 120, 240, 360, and 600 grit. Polishing was completed using 0.3 micron alumina particles suspended in water on a rotating cloth wheel. The samples were etched for approximately 1-1/2 minutes in a room temperature saturated solution of picric acid in water. The volume fraction of primary solid particles was determined using a standard two-dimensional systematic point counting procedure.[11]

b. Static Operation

Volume fraction of solid from the static tests was determined from the cooling curves. The thermocouple trace from each of the trials was extrapolated to the experimentally determined solidus temperature. It was assumed that the volume fraction of solid was a linear function of solidification time between the liquidus and the solidus.

2. Shear Rate

The shear rate in the mixing chamber is a function of the rotor geometry, the clearance between the rotor and the mixing chamber walls and the rotation speed.

The average shear rate in the annulus of the mixing chamber can be calculated from the following equation[12] (ignoring axial flow of material):

$$\dot{\gamma}_{Avg} = \frac{2\Omega_o}{(1-\kappa^2)}\,\kappa \qquad (1)$$

where $\dot{\gamma}_{Avg}$ ≡ average shear rate

Ω_o ≡ angular velocity

κ ≡ ratio between the equivalent radius of the square rotor and the radius of the mixing chamber

In the high temperature continuous Rheocaster, κ = 0.89 and $\dot{\gamma}_{Avg}$(in sec^{-1}) = 0.90 x rotation speed (in RPM).

Rotation speed was measured directly from the rotor assembly with a tachometer.

3. <u>Solidification Rate</u>

The average solidification rate is expressed as fraction solidified per unit time. In the continuous production runs it is calculated from the following equation:

$$(df_s/dt)_{Avg} = \frac{f_s\dot{Q}}{\rho V} \qquad (2)$$

where $(df_s/dt)_{Avg}$ ≡ average solidification rate (min^{-1})

f_s ≡ measured volume fraction of solid

$\dot{Q}$ ≡ slurry flow rate (lbs/min)

ρ ≡ metal density (lbs/in^3)

V ≡ volume of mixing chamber (in^3)

In the high temperature continuous Rheocaster:

$$(df_s/dt)_{Avg}(min^{-1}) = \frac{f_s\dot{Q}(lbs\ min^{-1})}{0.82\ (lbs)} \qquad (3)$$

In the static, viscometer-like tests, the average solidification rates were calculated by dividing the calculated volume fraction of solid at the time the trial was stopped by the time it took to cool to that point from the liquidus.

Average cooling rates can be calculated by multiplying the average solidification rates by the freezing range of the alloy. In this work, reference is made to average solidification rates rather than average cooling rates. Solidification rate is the more meaningful concept when only partial solidification is occurring. Cooling rate within the liquid-solid region can vary more than solidification rate in a system in which heat is extracted at a constant rate.

4. Particle Size and Entrapped Liquid

The water-quenched samples from the continuous production runs were examined further to determine an effective radius is the radius of uniformly sized spherical particles having the same surface to volume ratio as the primary solid particles in the Rheocast 4340.

Areas near the edges of the water-quenched samples were chosen for examination. In these areas, the quench rate was higher and individual particles are more distinct. The fraction of solid of these areas is generally lower than the overall fraction of solid, but this was corrected as described below.

For each area examined, volume fraction of solid, f_s, and volume fraction of entrapped liquid, f_{el}, were determined using a two-dimensional systematic point counting method. The particle surface to total volume ratio, S_v, was calculated using a standard line intercept procedure.[11]

Correction was made for fraction of solid by calculating the ratio of entrapped liquid to primary solid for each area examined in a sample, taking the average of this ratio, and multiplying by the overall sample fraction of solid. This calculation is given by the following equation:

$$(f_{el})_T = \frac{\sum_{i=1}^{n} (f_{el})_i/(f_s)_i}{n} (f_s)_T \qquad (4)$$

where $(f_{el})_T \equiv$ overall volume fraction of entrapped liquid

$\frac{(f_{el})_i}{(f_s)_i} \equiv$ the ratio of entrapped liquid to primary solid in area i

$n \equiv$ number of areas in the sample that were examined

$(f_s)_T \equiv$ overall volume fraction of solid in the sample.

The average primary solid particle surface to volume ratio was calculated according to the following equation:

$$(S_v)_s = \frac{S_v}{(f_{el})_T + (f_s)_T} \qquad (5)$$

where $(S_v)_s \equiv$ average surface to volume ratio of the primary solid particles

S_v ≡ primary solid particle surface to total volume ratio.

The average effective particle radius was then calculated by assuming that the particles are spherical with a surface to volume ratio equal to 3/r:

$$r = \frac{3}{(S_v)_s} \tag{6}$$

where r is the effective average particle radius.

5. Viscosity

The torque required to turn the rotor in the high temperature continuous Rheocaster, neglecting the downward flow of metal and the contribution of the liquid metal in the upper chamber is related to the slurry viscosity as shown in the following equation[12]:

$$T = \frac{4\pi\kappa^2 R\Omega_O}{1-\kappa^2} \int_{z=0}^{z=L} \eta(z)dz \tag{7}$$

where R ≡ radius of the mixing chamber

z ≡ distance from the top of the mixing chamber

L ≡ total length of the mixing chamber

$\eta(z)$ ≡ apparent viscosity of the material in the mixing chamber.

The viscosity distribution in the mixing chamber is not known at this time and the mean viscosity:

$$\bar{\eta} = \frac{\int_{z=0}^{z=L} \eta(z)dz}{L} \quad (8)$$

is the viscosity that is considered in this work.

Theoretically, it is possible to calculate the torque from the amperage reading and characteristics of the motor and the speed controller. In general, amperage is directly proportional to torque and independent of rotation speed. The proportionality constant is difficult to calculate because of the way in which the controller alters the wave form and the ammeter averages that wave form. For this reason, the relationship between viscosity and amperage was experimentally determined.

A simulated Rheocaster was built using the same alumina combustion tubes for the mixing chamber as is used in the production Rheocasters. A chromel-alumel thermocouple was cemented in a hole through the midpoint of the wall of the tube with the bead protruding 0.05 cm into the mixing chamber to monitor the fluid temperature. The model Rheocaster was assembled on the Rheocaster frame so that the standard rotor assembly and drive system could be used.

Two viscosity standards complying with ASTM specifications and supplied by the Cannon Instrument Company were used as fluids in the mixing chamber. Viscosities ranging from roughly 4 poise to 80 poise could be obtained by controlling the temperature of the fluid in the mixing chamber.

The rotor was turned at 400, 600, 800 and 1000 RPM and the amperage required to turn the rotor and the fluid temperature were recorded. The viscosity of the fluid was

then determined from the information supplied with the viscosity standards on the relationship between temperature and viscosity. The results of these experiments are listed in Table 1.

Since amperage is directly proportional to torque and torque is proportional to rotation speed times viscosity, as shown in Equation 7, a plot of rotor drive amperage versus a torque parameter including rotation speed and viscosity should yield a straight line. Figure 5 shows the results of the amperage versus viscosity trials plotted in the above manner. The equation of the line in Figure 5 as determined by linear regression analysis of the data is:

$$(\text{RPM}) \times \bar{\eta} = 2.39 \times 10^{4} \times \text{amperage} \qquad (9)$$

Amperage readings were converted to apparent viscosities using the above equation.

6. <u>Composition</u>

Chemical analyses of several water-quenched samples of Rheocast 4340 and a piece of the feed stock were performed by Arnold Greene Testing Laboratories to determine if the metal composition is affected by the Rheocasting process.

C. Results

1. Microstructure and Composition of Water-Quenched Rheocast AISI 4340

Typical microstructures of water-quenched samples of

Rheocast AISI 4340 are shown in Figure 6. Figure 6a shows the center of a water-quenched drop while Figure 6b shows the microstructure at the edge of the sample where fraction of solid is lower than in the center and where primary solid particles are more distinct because of the higher cooling rate experienced during solidification.

The microstructure of the water-quenched samples of Rheocast 4340 is similar to that of other Rheocast alloys. It consists of a relatively homogeneous distribution of non-dendritic primary solid particles in a matrix of quenched liquid.

The presence of a low primary fraction of solid layer at the edges of the samples, as shown in Figure 6, has not been reported previously for water-quenched samples. It has been observed at the edges of Thixocastings.[3,13] It has been suggested that the presence of such a layer is a rheological phenomenon associated with flow of particulate streams.[13] Water-quenched drops, however, do not experience the severe flow conditions that metal does being forced into a die.

The composition of the 4340 feed stock and two water-quenched samples, one taken early in a run and one taken after five hours of semi-continuous operation, are given in Table 2. Rheocasting does not significantly alter the composition of the feed stock. The composition of Rheocast 4340 is well within specifications.

2. Rotor Drive Amperage Versus Fraction of Solid

Two sets of experiments were run to examine the

relationship between the amperage required for the motor to drive the rotor at a given speed and the fraction of solid of the Rheocast 4340 produced. The experimental procedures and the method of determining fraction of solid for the continuous production runs and the static tests were described in the previous section.

a. Continuous Production

There is a close correlation between the volume fraction of primary solid in 4340 slurry exiting from the high temperature Rheocaster and the amperage drawn by the motor to turn the rotor at a given speed. The shape of the curves in Figures 7 and 8 is as expected, based on previous work with Sn-15% Pb slurries.[7-10] The fact that curves of the type shown in Figures 7 and 8 can be generated from continuous production runs indicates that the method used to operate the high temperature continuous Rheocaster does allow the output to be reasonably and reliably controlled.

In general, there is little increase in rotor drive amperage until the metal at the mixing chamber exit is roughly 25% solid. At fraction of solid above 0.25, the amperage rises rapidly with increasing fraction of solid. The rate at which the amperage increases with fraction of solid is higher in slurries produced with low rotation speeds than in those produced with higher rotation speeds.

The points plotted in Figure 7 represent data collected from runs made in four separate Rheocasters with average solidification rates of between 0.66 min^{-1} and 0.95 min^{-1} and a rotation speed of 800 RPM. Rotor drive

amps increase from 0 to 1.5 as fraction of solid increases from 0 to roughly 0.55 in Rheocast 4340 slurries produced under these conditions. There appears to be no significant difference between the results of runs made in different furnaces.

Figure 8 shows the data points collected from runs made in two separate furnaces with a rotation speed of 600 RPM and average solidification rates of 0.57 min^{-1} and 0.66 min^{-1}. Again, there are no significant differences attributable to the use of the different furnaces. Rotor drive amps increase from 0 to 1.6 amps as fraction of solid increases from 0 to roughly 0.45.

b. <u>Static Tests</u>

The relationship between rotor drive amperage and slurry fraction of solid can also be determined from static, viscometer-like tests. The results of these tests are similar to those obtained from continuous production runs. Amperage increases with increasing fraction of solid with an increasing rate of rise at higher fractions of solid. Amperage increases faster at low shear rates or high solidification rates than at high shear rates or low solidification rates. Figure 9 shows the results from static tests made at 600 RPM with average solidification rates of 0.95 and 0.59 min^{-1} and at 800 RPM with solidification rates of 0.76 and 0.38 min^{-1}. Figures 10 and 11 show that the results of static tests and continuous production runs with equivalent rotation speeds and solidification rates are in very good agreement. The implication of this is that the relatively simple static tests can be used to generate operating curves for continuous Rheocast 4340 production.

3. Viscosity Versus Fraction of Solid

Rotor drive amperages from the continuous production runs and the static tests were converted to viscosities using the procedures described in Section B-5. The results are shown in Figures 12 and 13.

The relationship between viscosity and fraction of solid of Rheocast AISI 4340 is qualitatively similar to that in Sn-15% Pb slurries.[7-10] In both alloys, viscosity increases at an increasing rate with increasing fraction of solid. For a given fraction of solid and solidification rate, a high shear rate produces a lower viscosity slurry than does a low shear rate. For example, a 4340 slurry that is 45% solid has an apparent viscosity of roughly 15 poise with a shear rate of 900 sec^{-1}, 25 poise with a shear rate of 720 sec^{-1}, 60 poise with a shear rate of 540 sec^{-1}, and 100 poise with a shear rate of 360 sec^{-1} when solidified at rates of between 0.43 and 0.82 min^{-1}. A high solidification rate produces a higher viscosity slurry of a given fraction of solid than does a low solidification rate with the same shear rate.

Viscosities of Rheocast 4340 slurries are of the same order of magnitude as those of Sn-15% Pb slurries at the same fractions of solid.[7-10] However, quantitative comparisons between the two were difficult to make because of the different method in which the viscosities of the two alloys were measured.

4. Effective Particle Size

The effect of slurry fraction of solid and shear rate

on the average primary solid particle size and the effect of particle size on slurry viscosity for Rheocast 4340 slurries have been found to be similar to those reported for Sn-15% Pb slurries[9,10] and 304 stainless steel slurries.[14]

Average particle sizes in Rheocast 4340 slurries produced within the range of solidification rates and shear rates employed in this work are roughly the same as those calculated from data on 304 stainless steel slurries produced under similar operating conditions.[14] Particle sizes in the 4340 slurries produced in this work are approximately three times those reported for Sn-15% Pb slurries produced at about the same solidification rate.[9,10,15]

a. Effective Particle Size Versus Fraction of Solid

Figure 14 shows the relationship between effective primary particle size and fraction of solid of Rheocast 4340. Each point represents an average of several samples at the appropriate shear rate and fraction of solid. In general, particle size appears to remain essentially constant up to fractions of solid of 0.25 after which it increases with increasing fraction of solid. In Rheocast slurries produced with an average shear rate of 720 sec^{-1} and solidification rates of between 0.66 min^{-1} and 0.95 min^{-1}, the effective particle size increases from 110 microns at 25% solid to 160 microns at 53% solid. Figure 15 is a series of micrographs which illustrate the increase in effective particle size with increasing fraction of solid.

The finding that primary solid particle size

increases with increasing fraction of solid in Rheocast 4340 agrees with the results of previous studies of Rheocast Sn-15% Pb[3,9,10] and Rheocast AISI 304 stainless steel.[14] Growth of primary solid particles can occur by a coarsening mechanism similar to that proposed for coarsening of dendritic structures, a process similar to the Ostwald ripening mechanism, and the coalescence and agglomeration of particles. Because these processes are time dependent, and because high fraction of solid slurries have a longer residence time in the mixing chamber than do low fraction of solid slurries, average particle sizes are larger in high fraction of solid slurries than in low fraction of solid slurries.

b. Effective Particle Size Versus Shear Rate

The effect of shear rate on effective particle size is shown in Figure 16. At fractions of solid above about 0.25, an increase in shear rate results in a decrease in effective particle radius. The effect of shear rate on particle size is greater at high than at low fractions of solid. In 46% solid slurries produced at 400 RPM, the effective particle radius is roughly 185 microns. In 46% solid slurries produced at 800 RPM, the effective particle size is 135 microns. The microstructures shown in Figure 17 illustrate the effect of shear rate on effective particle size. Previous work has shown that this same relationship between shear rate and particle size exists for shear rates between 230 and 750 sec^{-1} in Rheocast Sn-15% Pb slurries solidified at a rate of 0.01 min^{-1}.[7,10] There are conflicting reports[9,15,16,17] on the effect of shear rate on particle size in Rheocast Sn-15% Pb solidified at rates

between 0.01 min^{-1} and 2.0 min^{-1}, but no effect has been observed with solidification rates higher than 2.0 min^{-1}.(9,16,17)

The relationship between shear rate and particle size is probably a result of the effect of shear rate on particle coalescence. Joly[9] has argued that high shear rates tend to prevent the formation of welds between particles. If this is true, at high shear rate, there should be very little particle agglomeration and, therefore, very little shear rate effect on particle size. Figure 16 indicates that the effect of shear rate on particle size in Rheocast 4340 diminishes at shear rates above 900 sec^{-1}.

c. Effective Particle Size Versus Solidification Rate

No effect of solidification rate on primary solid particle size in Rheocast 4340 was observed within the range of solidification rates employed in this work. The scatter of particle sizes found in this work is about the same size as any expected variation due to a cooling rate effect. The average primary solid particle diameters in Rheocast 4340 are approximately the same size as primary dendrite arm spacings in 4340 solidified dendritically at about the same rate.[18] A correspondence between primary solid particle size and primary dendrite arm spacing has been reported for Sn-15% Pb and for cobalt based X-40 superalloy.[15]

d. Effective Particle Size Versus Viscosity

In Rheocast 4340 produced within the range of

solidification rates employed in this work, small particles are associated with low viscosity slurries. In general, Rheocast 4340 subjected to high shear rates has a lower viscosity and a smaller particle size than material subjected to lower shear rates. This same effect has been observed in Sn-15% Pb slurries[9,10] and in suspensions of quartz particles in water.[19] The increase in viscosity with increasing particle size was attributed in the latter work to the increased magnitude of the inertial forces involved in the collisions between the larger particles.

In particle size effect on viscosity partially explains the shape of the viscosity versus fraction of solid curves shown in Figures 12 and 13. As fraction of solid increases, the primary solid particle size also increases (Figure 14). The viscosity increase is greater than it would be with no particle size increase. The fact that particle growth with increasing fraction of solid is less at high shear rates than at low shear rates results in a lower rate of viscosity increase in slurries subjected to high shear rates. At very high shear rates, above 900 sec^{-1}, one would expect very little effect of particle size on the rate of viscosity increase because particle growth is apparently prevented at high shear rates (Figure 16).

III. THIXOCASTING

The aim of this part of the program has been to develop and analyze the high temperature Thixocast system for machine casting AISI 4340 low alloy steel. To that end, work has proceeded along several lines:

1. system development, including design and testing of equipment,

2. pilot plant operation of the system to demonstrate feasilibity and to generate sufficient data for subsequent analysis,

3. investigation of cast part quality, and

4. investigation of machine component wear.

The results of this work, together with those pertaining to the Rheocaster, were then used as a basis for an economic analysis of the entire Rheocast/Thixocast process as it applies to the production of small ferrous parts. The economic analysis is included in a later section of this report.

A. SystemsDevelopment

Previous work at M.I.T. has demonstrated the technical feasibility of producing stainless steel parts with the Thixocast system.[4,5,6] The basic system used in that work, primarily the reheating system, has been modified to allow the casting of AISI 4340 low alloy steel.

The reheat system consists of an inductively powered reheat furnace, a Softness Indicator, which probes the reheating charge and indicates when it has reached the desired fraction of solid, and a transfer mechanism. The reheat station is shown in Figure 18.

The reheat furnace, shown schematically in Figure 19, consists of a 21-turn induction coil wrapped in Silver-flex insulation and compressed between two transite plates. The coil is approximately 7-3/4" long and 3" in diameter. A 1/4" thick, 2-1/2" ID by 8-1/4" long mullite tube lines the inside of the coil. The entire assembly is held together and attached to a transite shelf by four external brass rods. The reheat furnace is powered by 60 KW, 3 KHz power supply manufactured by Inductotherm Corporation.

The automatic transfer mechanism consists of a clay-graphite pedestal seated on two transite disks and two aluminum plates. The entire assembly is operated by a 1" bore diameter air cylinder. In the up position, the bottom of the furnace is sealed by the upper transite disk. When opened, the pedestal lowers 8 inches, allowing for easy removal of the crucible containing the reheated ingot.

The top of the furnace is sealed by a shaped fire-brick plug, coated with Aluma 65 firebrick cement. A protective atmosphere of argon-4% hydrogen gas and the Softness Indicator probe pass through a 1/4" diameter hole in the center of the firebrick.

The Softness Indicator consists of a 1/8" diameter, 6" long solid alumina rod, held in a pin vise attached to

the end of a 1/2" diameter stainless steel rod. The steel rod passes through two linear roller bearings, and is connected to a 7/16" bore diameter air cylinder. Pressure on the cylinder is adjusted with an air pressure regulator, and can be monitored by a 0 to 60 psi gauge. Probe penetration distance can be accurately measured by two limit switches placed adjacent to the probe shaft, and tripped by a pointer on the shaft.

The entire system can be operated in either a manual or a semi-automatic mode. In the manual mode, each function can be operated independently. This includes activation of the loading pedestal, activation of the probe assembly, and activation of the induction power supply. The power input to the coil can be adjusted by a power rheostat on the control panel.

In the semi-automatic mode, the entire assembly follows a predetermined operating schedule. After the crucible containing the ingot is placed on the pedestal and the semi-automatic cycle is initiated, the transfer mechanism raises the crucible into the furnace and seals the bottom of the furnace. When the furnace has been completely sealed, the probe is activated and power is delivered to the induction coil. By the use of time delayed control relays, a two-stage heating cycle is possible. Initially, a high heating rate is activated to raise the temperature of the ingot very rapidly to near the solidus temperature. After a predetermined time, the power to the coil drops, resulting in a slower heating rate and a uniform temperature profile in the ingot as it approaches the liquid-solid casting temperature.

When the probe is activated, it lowers and firmly contacts the top of the reheating ingot. The limit switch housing is then either raised or lowered until the upper switch has closed, as indicated by a control light. As the ingot begins to melt, the probe starts downward, penetrating the softening ingot. When the lower limit switch is tripped, power to the coil is shut off, the transfer mechanism is lowered, and the probe is retracted. Separation between switches, and consequently probe penetration distance is adjustable between 0 and 1 inch. By using the semi-automatic cycle, operator control is minimized, and reheating characteristics are repeatable from cycle to cycle.

1-1/4" diameter x 1-3/4" long Rheocast ingots were reheated in 1-3/4" inner diameter, 1/4" wall thickness clay-graphite crucibles. Crucibles were cut to length such that the Rheocast ingot just reached the top of the crucible. Due to the thixotropic nature of Rheocast metals, semi-solid ingots maintain their shape at very low fractions of solid until sheared, and no mold wash was required to coat crucible walls.

Experiments were conducted with the reheat furnace to determine the effect of heating rate on the temperature gradients in a reheated slug. A power setting of 16 KW was found to provide the best combination of rapid reheat time and minimum temperature gradient. The maximum temperature difference in a slug heated to just below the solidus with a power setting of 16 KW was found to be 5°C. Visual examination of ingots heated to the liquid-solid casting temperature at this rate showed that ingot reheating was good, with no fully melted or completely solid areas.

The initial rapid heating cycle was then added to the semi-automatic mode of the reheat furnace. Effort was directed at maximizing the rate and duration of maximum heating to minimize the total reheating cycle time without destroying the final uniform reheated characteristics resulting from 16 KW power setting. Optimum results occurred when ingots were reheated at 40 KW for 25 seconds, at which time the power dropped to 16 KW for the remaining time until the ingot had reached the liquid-solid casting temperature.

Reheated Rheocast AISI 4340 ingots were charged to the shot chamber of a commercial B&T Greenlee die casting machine, shown in Figure 20. The machine is a horizontal, cold chamber model, capable of providing 125 tons of locking force to the dies. A 20 HP motor, driving a Vickers V400 Vane Pump maintains hydraulic line pressure a 1200 psi maximum. The hydraulic system includes an accumulator and a shot intensifier, capable of increasing hydraulic line pressure to 2000 psi maximum at the end of a shot stoke.

A 1-3/8" diameter, water-cooled plunger tip is hydraulically powered by a 4" bore diameter shot cylinder, resulting in a pressure multiplication of 8.46 to 1 at the plunger tip. Plunger speed may be varied up to a maximum of 36 inches per second. A 3-1/2" outside diameter shot sleeve was heated with a resistance band heater. Nominal operating temperature was 400°C. Hardened AISI H-13 die steel (0.40 C, 0.40 Mn, 1.10 Si, 5.00 Cr, 1.10 V, 1.35 Mo, weight percent) was used for both the plunger tip and the shot sleeve. Commercial plunger tip lubricant was applied between shots.

Die lock-up time after injection could be adjusted between 0 and 30 seconds by an automatic cycle timer. An external water spray system for die cooling, shown in Figure 21, was coupled to the control system of the die casting machine. The cooling system consists of six external water lines with full cone impactor type spray nozzles which directly water spray each die cavity insert immediately following part ejection. A colloidal base graphite mixed with water was used as a die release agent, and was applied by spray after water-cooling. Die faces were dried with forced air before lock-up and initiation of the next cycle.

A Honeywell four channel die casting system monitored machine conditions during the casting sequence. The system included a model 1508B Visicorder Oscillographic which displays output from a position channel, a velocity channel and two pressure channels. The position and velocity transducers were connected to the shot piston, and the two pressure transducers were connected to the front and back hydraulic lines feeding the shot cylinder. As a result, plunger speed and position, together with the front and back pressures on the shot piston were displayed simultaneously on the same chart.

A Department of Defense part, procured as either an investment casting or as a forging, was selected to investigate the feasibility of machine casting a low alloy steel by the Thixocast process. Specifications for the part, the M-85 Pawl, cartridge stop, are shown in Figure 22. The actual forged and finished part, as received from AMMRC, is shown in Figure 23.

Die cavity inserts and runner pad inserts were held in a 9-7/8" x 11-7/8" D.M.E. standard mold base. Both the stationary and moving cavity retainer plates were 1-3/8" thick, AISI H-13 die steel. Dies were designed such that no part of either cavity retainer plate was in direct contact with hot metal during the casting sequence. Maximum stroke of ejector pins was 1-13/16". No die heaters or internal water-cooling lines were included in the mold base.

Elbrodur RS, an age-hardening chromium copper with addition of zirconium, manufactured by Kabel and Metallwerke, West Germany, and distributed in the United States by Eltek Corporation, was selected as the cavity insert material. The RS alloy series is a high conductivity grade used primarily as electrode material for resistance seam welding of steel. It is known to withstand high stresses and is almost free from susceptibility to cracking.

Cavity insert rounds were turned from hardened, 4" diameter drawn rod stock. Die cavities were prepared by EDM (electro-discharge machining) in two 3-1/2" diameter x 1-3/8" thick die insert rounds. Die cavities were prepared to cast the M-85 pawl to net shape, excluding the one through hole, which was replaced with locating bosses in both die cavities.

Runner pads were prepared in AISI H-13 die steel. The die cavity was fed by a 2" long x 3/8" radius semicircular cross-section runner, machined in the moving die half runner pad. The cavity gate, centered on the parting line, was 1/8" wide x 1/8" deep in both die halves, and was oval shaped in cross-section. In this manner, the runner cross-section of approximately 0.127 in^2 reduced to 0.028 in^2 at the gate, representing a 1 to 0.220 reduction of area.

Three overflows surrounded the part cavity in the moving die half. Ejection was accomplished by four 1/4" diameter standard hot work ejector pins, one placed on the runner, and one placed on each overflow. All ejector pins were recessed 1/4" to minimize wear. No vents were prepared in the die assembly, venting being accomplished through the parting line and ejector pin hole clearances only.

A photograph of the entire casting, including overflows, runner, and biscuit is shown in Figure 24. The machine cast M-85 Pawl is shown in the as-cast condition in Figure 25 and in the finished condition in Figure 26.

System variables, including probe pressure, plunger speed and plunger pressure were adjusted to optimize casting quality. Several die casting runs were made in which each variable was adjusted independently to determine its effect on casting quality. With the Softness Indicator set at 1/2" probe travel, probe air pressure of 20 psi resulted in consistent die fill out. Ingots were die cast with plunger speed set at 35 in/sec (1863 in/sec gate velocity) and plunger hydraulic line pressure set at 1200 psi (10,155 psi plunger tip pressure). No intensification was necessary.

In order to minize heat transfer to the dies during a casting sequence, die lock up time after full pressurization was decreased as much as possible. Since the dies not only act as the mold which produces net part shape but also as heat exchangers for the solidification process, a die casting must remain in the die until a sufficiently thick skin has solidified to allow ejection of dimensionally accurate components. Further time in the dies is unnecessary, and may be detrimental to ultimate die life. Die

lock-up time after full pressurization was reduced to 0.4 seconds, sufficient time to allow ejection of dimensionally accurate parts.

After castings were ejected, die inserts were immediately water spray cooled. Spray initiated when the dies were fully opened, and lasted approximately 5 seconds. Dies were operated at approximately 50°C ambient temperature.

A typical Visicorder trace, showing machine parameters during a shot sequence is shown in Figure 27. Several steps in the shot sequence have been labeled on the chart.

Initially, castings were air-cooled; however, to avoid stress cracking they were later placed in vermiculite and slow-cooled.

B. Pilot Plant Operation

The high temperature Thixocast system for AISI 4340 was operated on a pilot plant basis to demonstrate feasibility and determine process variables, especially die life. Full day production runs were conducted on a repeated basis. Two operators were required, both for safety and to record data between shots. One operator controlled the reheating system and the shot end of the die casting machine. Responsibilities included loading the furnace, adjusting the probe assembly, charging the reheated semi-solid ingot to the shot cylinder, and cleaning and lubricating the shot sleeve after injection. The second operator's responsibilities were the die half of the die casting machine and inspection and handling of the castings made. This included removing the casting from the machine, inspecting it, and placing it in vermiculite for

slow cooling and drying and lubricating the dies. Castings were evaluated as either fillouts, semi-fills (in which case die life may have been affected but a sound casting did not result) and non-fills.

A total of 2200 shots were attempted, with 1726 castings (78%) passing visual inspection after ejection. Inspection yields appear to be most sensitive to reheating characteristics and Rheocast ingot quality. A maximum daily inspection yield of 99% was recorded.

The maximum production rate possible was 40 shots per hour. Production rate is limited by the single shot reheating characteristics of the furnace. Typically, ingots reheated to the liquid-solid casting temperature in 1 minute and 20 seconds, representing the bulk of the time involved in a casting sequence.

Machine components, especially die inserts, were inspected daily following each production run. To better evaluate component wear during the entire process, no touch-up or repair of machine components was attempted.

C. Casting Properties

Following production runs, castings were examined by various techniques to evaluate cast part quality. The majority of the cast part properties were evaluated on 100 parts randomly selected between shots 718 and 1724. These properties, including hardness, radiographic rating, fraction of solid, and volume percent porosity have been tabulated in Appendix A. Additional castings were selected for radiography and chemical analysis.

1. Microstructure and Composition of Thixocast AISI 4340

Metallographic specimens were cut from the gate area of runners to investigate structure related properties. SAmples were mounted in bakelite, and ground in successive steps on 120, 240, 360, and 600 grit wet silicon carbide grinding wheels. They were polished using an aqueous solution of 0.3 micron alumina powder. Samples were etched by immersion for approximately one minute and 15 seconds in a room temperature saturated solution of picric acid in distilled water.

Typical microstructures of both Rheocast and Thixocast AISI 4340 are compared to conventionally cast AISI 4340 in Figure 28. The structures are characteristic of all Rheocast and Thixocast materials. The quenched Rheocast structure consists of rounded nondendritic, primary solid particles in a matrix of quenched liquid. Due to slower cooling rate, the Rheocast ingot structure is characterized by coarsened primary solid particles. The appearance of martensite in the Rheocast ingot structure results from etching effects. The Thixocast structure consists of irregularly shaped primary solid particles in a rapidly quenched liquid. Due to the rapid cooling rates experienced in copper dies, fine dendrites and very well-defined primary solid particles result.

Chemical compositions were determined at various stages in the Thixocast process. Analyses were performed by Arnold Greene Testing Laboratories, Natick, Massachusetts.

The composition of 4340 is not significantly affected

by either Rheocasting or Thixocasting. The compositions of the as-received 4340 rod stock, two water-quenched samples, one taken very early in the Rheocast run and one taken after approximately five hours of semi-continuous operation, and a Thixocast 4340 are given in Table 2.

2. Fraction of Solid

The volume fraction of primary solid particles in the metallographic samples cut from the gate area of the runners was determined by a standard two-dimensional point counting method.[11]

The distribution of fractions of solid measured in 50 randomly selected castings is shown in Figure 29. The average fraction of solid measured was 0.405, with a standard deviation of 0.131. In general, the fraction of solid was uniform across each sample. Occasionally, small, fully liquid areas were observed.

3. Porosity

Casting porosity was evaluated by x-ray radiography. 383 castings were radiographed and rated according to the radiographic scale shown in Figure 30. The resulting distribution of radiographic ratings is shown in Figure 31.

4. Hardness

Hardness measurements were taken on both air-cooled and vermiculite-cooled castings. The average hardness measured on 35 air-cooled castings was R_c 50, whereas the

average hardness measured on 65 vermiculite-cooled castings was R_c 25.

Micro-hardness measurements for both primary solid particles and dendritic prior liquid areas were taken on Rheocast water-quenched samples, air-cooled castings, and vermiculite-cooled castings. Results have been tabulated in Table 3. In general, prior liquid areas have greater hardness than do primary solid particles.

5. Determined Cooling Rate During Solidification

During solidification, the cooling rate in the dies was determined by measuring secondary dendrite arm spacings at less than 1 mm from the casting surface, and converting to cooling rate according to published data. Murty et al[20] have reported secondary dendrite arm spacing vs. local average cooling rate data for AISI 4340 steel, and their data points have been included in Figure 32. Measured secondary dendrite arm spacings for Thixocast 4340 varied between 3.8 and 5.1 microns and including these points on the line generated by Murty et al[20] requires extrapolation over three orders of magnitude in cooling rate (°C/sec). Given the magnitude of this extrapolation, it appears that AISI 4340 Thixocast in copper dies experiences very rapid cooling rates during solidification, on the order of 10^4 °C/sec.

D. Machine Component Wear

Machine components subject to wear due to contact with semi-solid metal include the plunger tip, shot sleeve,

runner pads, and die cavity inserts. Of particular importance, due to their high cost and direct effect on casting quality, are the die cavity inserts. Therefore, wear on the plunger tip, shot sleeve and runner pads was evaluated on a final condition basis, while die cavity insert wear was evaluated on a per shot basis whenever possible.

Basic modes of die wear include heat checking and die parting line erosion. Quantification of these effects was possible by measuring the impressions left on cast parts, and correlating it to the shot history of the die. Parting line erosion was quantified by measuring the maximum flash thickness of a part. Heat checking, on the other hand, was quantified by measuring fin height on cast parts resulting from fill-out of a heat check crack in the die. In addition, dimensional stability of the dies was evaluated by measuring the dimensional stability of the cast parts produced through the die life casting runs.

1. Plunger Tip

As mentioned earlier, a water-cooled, hardened, AISI H-13 die steel plunger tip was used in this study. After 2200 shots, the plunger tip appeared to be in good condition, with a significant portion of its life still remaining. The final condition of the plunger tip is shown in Figure 33. Wear is limited to some scoring along the length of the tip, and heat checking on the end where the plunger tip is directly exposed to semi-solid steel during die filling.

2. Shot Sleeve

A hardened and nitrided AISI H-13 die steel shot sleeve was used in this study. Wear was limited to the die end of the shot sleeve, which represents the most severe environment. After charging a reheated semi-solid ingot to the shot sleeve, the plunger is activated and the ingot is pushed ahead of the plunger tip, filling out the die cavity. The biscuit, or remainder of the metal from which the die cavity is fed, remains in the shot sleeve end, until final solidification and ejection of the casting from the dies. Figure 34 shows a photograph of the shot sleeve end after 2200 shots. Heat checking begins at the corner, and proceeds radially outward. Checking is limited to the initial 1/4" of the shot sleeve length.

The extent of checking at the shot sleeve end can eventually handicap the ejection of castings from the die. However, due to the nature and extent of checking this does not appear to be a significant problem. No ejection problems were encountered over 2200 shots, and none would be expected for several thousand more shots.

A significant problem in high temperature, cold chamber die casting is shot sleeve warpage.[21,22] When a fully molten alloy with superheat is poured into a shot sleeve, it flows the entire length of the sleeve and covers the bottom before the plunger is activated. This results in thermally induced stresses in the sleeve.

Since the contact area between the sleeve and molten melt is on the bottom of the shot sleeve bore, that area

will be in compression due to thermal expansion, while the sleeve top will be in tension. This thermally induced loading over many cycles may eventually result in shot sleeve warpage.

No warpage was measured after 2200 shots when AISI 4340 was Thixocast. The shot sleeve bore was measured and remained true to + 0.0005" along its length. Due to Rheocast material's thixotropic nature, reheated ingots maintain their shape and do not flow along the bottom of the shot sleeve. Since the contact area between the shot sleeve and reheated ingot is small, heat transfer to the shot sleeve, and consequently thermally induced stresses are significantly reduced. This appears to be a significant advantage in die casting high temperature alloys by the Thixocast process.

3. Runner Pads

Runner pads were machined and hardened in AISI H-13 die steel. Figure 35 shows the final condition of the runner produced after 2200 shots. Due to the low operating temperature (~50°C) of the dies, heat checking in the runner pads is severe; no adverse effect on casting fill-out or ejection was observed during production runs. Flashing around runners was never encountered, and does not appear to be a significant area of concern for the Thixocast process for low alloy steel.

4. Die Cavity Inserts

Die cavity inserts were prepared in Elbrodur RS, an age hardening chromium copper with additions of zirconium. The higher thermal conductivity and lower coefficient of thermal expansion exhibited by Elbrodur RS

was expected to reduce heat checking from that expected in die steels.

As mentioned earlier, die insert wear was evaluated on a per shot basis, to give not only a history of die wear but also a rate of die wear during casting runs. Data pertaining to die insert wear has been tabulated in Appendix B.

A history of parts cast in the Elbrodur RS die cavity insert set is shown in Figure 36. Two types of wear modes are apparent, erosion along the die cavity parting line and cracking along corners in the die cavity. Neither mode appears to leave impressions large enough on the cast part to term the insert as failed.

Maximum flash thickness was measured on successive cast parts to determine the rate of parting line erosion. Results have been plotted versus number of shots in Figure 37. A maximum flash thickness of 0.020" was recorded after 2200 shots. However, the majority of the erosion occurred during the initial 500 shots, when flashing had reached a thickness of 0.017". Following the first 500 shots, erosion proceeded slowly, and at a relatively constant rate of 1.76×10^{-6} in/shot.

The height of the impression left on the castings from fill-out of the largest heat check crack (moving die insert, casting corner at the gate) was measured to determine the rate of crack growth. Results have been plotted versus number of shots in Figure 38. Since each point represents impression height, and the size of the impression may be limited by the degree of fill-out in a thin section, a smooth curve representing crack depth has

been traced through the maximum data points.

No cracking was observed until approximately the four hundredth shot. The maximum impression height measured at 2200 shots was 0.032 inches. While this may be the limiting mode of die wear, heat check cracking in copper dies appears to be extremely sensitive to die cavity configuration. Cracking only occurred at right angle, inside corners in the die cavity. Improved die design will undoubtedly decrease cracking and, ultimately, increase overall die life. By altering part design and including a radius at corners, die cracking in those areas may be reduced.

Dimensional stability of the die inserts through production runs is excellent. Part thickness (measured across the parting line) varied between 0.339" and 0.343". This was well within the specified tolerance of $0.343^{+0.000}_{-0.013}$. All other dimensions remained constant.

Die cavity inserts were initially hardened to R_B 65. An important consideration when using an age-hardening alloy such as Elbrodur RS as a die material is whether repeated exposure to elevated temperatures will result in significant overaging. Hardness measurements taken after 2200 shots indicate that overaging is not significant. The insert back remained at R_B 65, while the front parting line surface had increased slightly to R_B 67. Measurements in the die cavity were recorded at R_B 62.

IV. ECONOMIC ANALYSIS

In order to determine the feasibility of the Thixocast process for low alloy steel from a commercial point of view, an economic survey was conducted. A cost analysis model was developed to project and compare casting costs per piece with established methods of manufacture (e.g., investment casting).

While the pilot plant operation established at M.I.T. is adequate for experimental investigation of the process, several improvements must be made before the process may be economically implemented as a full-scale production operation. Basically, full-scale production would require a significant increase in production rate. This may be accomplished by scaling up the continuous Rheocaster, utilizing multiple cavity dies, and increasing the ingot reheating rate. These proposed modifications are dealt with in detail in later sections.

A critical influence on the process economics is casting quality and the severity of inspection criteria. Any component produced by a given forming process must meet certain specifications with respect to surface finish, metallurgical soundness, and mechanical properties, all of which are usually specified by the consumer. Since ferrous machine casting is not commercially practised in this country, there are no standards by which to evaluate casting quality. Consequently, this analysis assumes only a visual inspection after casting, with a rejection rate of 5%. No subsequent inspection steps (e.g., Magnaflux, radiography, etc.) have been included.

Additional inspection steps will obviously increase part manufacturing costs due not only to the addition of the inspection steps and their related costs, but also to the casting rejection rate of each additional inspection operation.

In addition, no provisions have been included for trimming, finishing, or heat treating. These too may be considered as subsequent operations and may be sensitive to part specifications and application. Consequently, this analysis deals only with manufacturing costs, and the final results represent the cost to cast an individual part.

Costs associated with the manufacturing of parts by the new machine casting process are subdivided into two sequences of operation:

a) Melting and Rheocasting, in which billets of the appropriate diameter to fit in the shot sleeve of a cold chamber die casting machine are Rheocast, and

b) Thixocasting, in which the Rheocast ingots are reheated by induction to the liquid-solid casting temperature and machine cast utilizing the surface quenched copper die technique.

The sequence of manufacturing operations is broken down into direct material and direct labor costs. Some of the usual manufacturing overhead costs (e.g., utilities, employee benefits, service and maintenance, etc.) are considered as part of direct materials or

labor costs. The other manufacturing overhead costs (e.g., administration, marketing, research, sales, profits, etc.) are unique to the manufacturer, and hence are not included in this cost analysis.

A. Rheocasting

The proposed Rheocasting system on which this analysis is based is composed of two similar Rheocasters, each capable of producing 500 pounds per hour of 4340 at 0.50 volume fraction of solid. In this manner, one Rheocaster may be operated while the furnace in the other is being rebuilt, resulting in minimum loss of time when a furnace fails.

The Rheocasters are fed by two 500-pound induction melting units which are arranged so that they can feed either of the two Rheocasters. The melting units are operated on an alternating basis such that one is feeding a Rheocaster while the other is melting the next 500 pounds of feed metal. Each melting unit is powered by a 100 KW induction power supply.

The Rheocast metal is collected in individual billet molds. The molds are cast iron and are mounted on a continuous belt which travels below the Rheocasters. Movements is indexed so that after one mold is full, the next one moves into place. The molds are cut with sufficient draft so that when they are inverted, the billets will fall out. While the molds are inverted, they are sprayed with a zirconia mold wash.

Operation of the proposed system is assumed to proceed around the clock, five days/week, fifty weeks/year.

The Rheocasting system requires three full-time operators; one to run the melting furnaces, one to operate the Rheocasters, and one to remove the billets and restock the melting units when empty. Additional labor is required for furnace construction and alignment.

Assuming that the yield of Rheocast billets is 80% of the 500 lb/hr capacity to allow for scrap losses and minor system malfunctions, the yearly production of Rheocast metal with the production schedule given above is 2,400,000 lbs/year.

Six cost categories for the production of Rheocast AISI 4340 have been determined. These include: (1) capital equipment, (2) furnace materials, (3) expendable materials, (4) labor, (5) base metal, and (6) melting.

Necessary capital equipment includes two Rheocasters, four 20 KW induction power supplies to power the Rheocasters, two 500-pound melting units powered by 100 KW power supplies, the automated billet casting system, and instrumentation for the total system. A list of estimated purchase and installation prices, write-off periods, and annual depreciation for this equipment is given in Table 4.

Capital cost per pound of Rheocast metal produced is obtained by dividing the amortized capital costs by the yearly production total. This result is a capital cost of $0.008 per pound.

The power supplies and melting furnaces are standard equipment and can be purchased from a number of

sources at near the estimated costs.

Rheocasters capable of producing 500 lbs/hr of Rheocast copper-based alloys have been built commercially for approximately $20,000 a piece. Since the major differences between these units and the proposed ferrous Rheocasters lie in the construction of the furnaces and not the Rheocasters themselves, it is assumed that this figure is a reasonable cost estimate for ferrous Rheocasters. The furnaces themselves are discussed in a later section.

An automated billet casting system is not commercially available at this time, but one can be easily conceived. A continuous belt carries individual cast iron molds underneath the Rheocasters. An indexing mechanism centers each mold in the metal stream. When an ingot is full, the track moves and the next mold is indexed into place. Assuming that 3" square molds with 1-3/4" in diameter by 3-2/3" high cavities (producing billets weighing 40 ounces) are mounted with a 1/8" separation, the continuous belt would move 3-1/8" every 18 seconds when Rheocast metal is produced at a rate of 500 pounds per hour. Movement of the belt could be triggered by the operator or be coupled directly to the metal flow rate.

Based on experience gained at M.I.T. during this program, it is estimated that the billets could be removed from the molds 3 minutes after filling. This would require the continuous belt extend 3 feet from the near Rheocaster. The total length of the belt would be approximately 20 feet. The molds would have roughly 15 minutes to cool between uses. Cooling of the molds would be increased by the zirconia mold wash spray.

It is estimated that an automated billet casting system such as this could be built for $20,000.

The maximum production rate that can be obtained in high temperature continuous Rheocaster at M.I.T. is roughly 250 pounds per hour. Relatively minor changes could be made to achieve production rates of 500 pounds per hour. An increase in the length of the alumina combustion tubes used as the mixing chambers from 6" to 10" would effectively double the volume of the mixing chamber and therefore the production rate. End effects on heat flow from the mixing chamber due to the liquid reservoir at the top and heated exit area would affect a proportionally smaller fraction of the mixing chamber.

Lengthening the mixing chamber would require a longer crucible and a longer rotor. A larger pressure head would also be required to maintain a uniform flow of slurry, because the increase in solidification rate will result in higher viscosity slurries.

The cost of materials in the present furnace is $225. Realizing that materials cost increases due to these minor modifications can be offset by large volume buying, an estimate of $250 per furnace is not unreasonable.

Rheocast furnace life is currently limited to roughly 15 hours. The conditions under which the unit is operated are far from ideal and far from those that would exist in the proposed system. The frequent cooling and heating cycles that are necessary with the present equipment result in a shift of the mixing chamber with

respect to the rotor, causing severe vibration problems and loss of control. A minor design change to hold the crucible more rigidly should extend furnace life considerably.

Wear of the ceramic parts in the furnace is minimal. Despite the necessity to seat the turning rotor directly on the exit part to stop flow numerous times, the visible wear on the rotor and exit area of the mixing chamber is less than that resulting from the initial rotor lapping.

Slag attack of the rotor at the melt line has been virtually eliminated through the use of the reducing gas shield in the upper chamber. This should not be the limiting factor in furnace life.

Considering that operation of the proposed Rheocasting system is continuous, requiring neither rotor-exit contact nor thermal cycling, an average furnace life of 48 hours should be easily obtainable.

Using this furnace life, a furnace materials cost of $250, and a Rheocast metal yield of 80% of the 500 pounds per hour capacity, the furnace materials cost per pound of metal produced is $0.013.

Expendable materials include primarily shield gases, zirconia mold wash, and the billet molds. Experience gained at M.I.T. during pilot production has indicated that these materials should add $0.008 per pound of Rheocast metal produced.

Labor costs apply to the three men necessary to operate the system. In addition, three man-hours are required to construct and set up each Rheocasting furnace. With a labor rate of $15.00 per hour, including manufacturing overhead and benefits, labor costs will be $0.115 per pound of Rheocast metal produced.

In an investment casting foundry, it costs $0.274 per pound to make up 4340 alloy. This figure includes the scrap metal prices plus the cost of additions necessary to adjust the composition.

It costs about $0.060 per pound to melt steel in a 500-pound melting unit in an investment casting foundry. This figure includes labor and overhead, furnace linings, melt losses, and other associated costs. Subtracting the expense of labor and overhead, which has been included under labor costs in this analysis, yields a melting cost of $0.023 per pound of Rheocast metal produced.

A summation of the costs from the six contributing categories, as shown in Table 5, yields a total cost of $0.441 per pound of Rheocast AISI 4340.

B. Thixocasting

This analysis is conducted on a per die casting machine basis. It assumes that the operation proceeds around the clock, 5 days/week, for 50 weeks/year. Each machine would require one full time operator, while each 6 machines would require one full time maintenance person. Operators would be generally responsible for the casting operation, while maintenance personnel would be responsible

for general maintenance of the die casting machine and its associated equipment, die removal and replacement, and furnace repair. In this manner, each machine would require 28 man-hours/day to operate the Thixocast process.

Productivity will directly affect individual cast part costs. A production rate of 120 shots/hour has been assumed. Maintaining this rate for 20 hours/day (4 hours/day has been assumed for labor break time and maintenance down time), over the given operating schedule, results in a productivity of 600,000 shots/year.

Seven cost categories for machine casting by the Thixocast process have been determined. These include: (1) capital equipment, (2) additional materials, (3) labor, (4) expendable materials, (5) reheating energy, (6) Rheocast metal, and (7) machine components. Each item is discussed further below.

Capital equipment costs are calculated and amortized over the estimated life cycle of the components. Total annual capital equipment costs are given in Tables 6 and 7. Capital equipment includes a suitable sized cold chamber die casting machine and induction power supply. It would also include an automatic mold wiping system to strip, water-quench, dry and lubricate the dies between shots. Two fully prepared mold bases have also been included as capital equipment since they are expected to last the life of the die casting machine. The use of two mold bases is expected to minimize down time due to die replacement. While one die set is in operation, the other set may be replaced with new inserts and prepared for the machine.

A continuous, tube radiation furnace for rapid reheating of Rheocast 4340 steel to the liquid-solid casting temperature is also included as capital equipment. Figure 39 is a schematic cross-section of such a furnace. The furnace is 10 feet long and is capable of reheating 40-ounce ingots of Rheocast AISI 4340 to approximately 0.55 fraction of solid at a rate of 120 ingots per hour.

The ingots are reheated by heat transfer (primarily radiative but with some convective effect) from a graphite susceptor which is heated by induction to a controlled temperature of 2642°F. (approximately 50% solid for AISI 4340). The temperatures of ingots travelling through such a furnace at a rate of 9 inches per minute as a function of time and distance travelled in the furnace are shown in Figure 40. The description of the methods used to generate these curves is given in Reference 23.

It is estimated that a reheating station of this kind would cost $10,000, including the continuous feed furnace and the necessary control system.

Included in the overall Thixocasting cost as additional materials are tools, die lubricants, shot sleeve lubricants, hydraulic fluids, and similar items necessary to maintain efficient operation of the Thixocast process. Additional materials costs are estimated at $1000/year.

Labor costs have been determined for the production schedule described above. Using a labor rate of $15/hour (including manufacturing overhead and benefits),

it is estimated that labor costs per die casting machine would be $105,000/year.

Expendable materials would include any items, excluding machine components, which is expended or subject to wear from repeated use. This includes furnace gas shielding, ingot boats, and furnace replacement parts. Based on the estimated costs resulting from the existing operation at M.I.T., expendable materials costs for full scale production would be approximately $0.10/shot.

Reheating energy costs have been estimated by calculating the theoretical energy required to reheat a 40 oz. Rheocast ingot of 4340 low alloy steel to 0.55 fraction of solid. Using an industrial electricity rate of $0.0043 per KW hour, and assuming 10% efficiency for the reheating furnace, reheating energy costs are estimated at $0.01/shot.

A significant portion of the total casting cost is the cost for Rheocast metal. Consequently, efficiency (maximizing casting weight to scrap weight) is very important. Essentially all Rheocasting costs for the metal returned to the Rheocaster as scrap must be absorbed in production costs and will be reflected as an increase in the casting cost for an individual part. Unlike a standard die casting practice where scrap is generally remelted and cast again, the Thixocast process requires that the scrap metal be reprocessed in the form of Rheocasting. This additional processing puts a premium price on Rheocast metal, and scrap generation must be minimized.

A design for a 16 cavity die set to cast the M-85 pawl cartridge stop is shown in Figure 41. The basic design utilizes 16 individual die cavity insert sets of Elbrodur RS copper alloy, fed by a single H-13 runner pad set. While Elbrodur RS is expected to extend ferrous machine casting die lives, runner pads are prepared in H-13 die steel to minimize heat transfer during die filling. The total shot weight of Rheocast AISI 4340 low alloy steel for this die configuration is estimated at 40 oz., of which 16 oz. would represent usable casting weight.

The remaining 24 oz. would be generated as scrap. Of that weight, 22 oz. is assumed returnable to the Rheocaster. 5% of the metal (2 oz.) is assumed to be lost in the processing as flash, grindings, etc. Casting material costs are estimated as ingot weight times Rheocast alloy costs less returnable scrap weight times base alloy cost. Using the previously given figures of $0.274 per pound of 4340 base alloy and $0.441 per pound for Rheocast 4340, the Rheocast metal costs for Thixocasting are estimated to be $0.726 per shot.

Machine components remain the single most critical cost for machine casting ferrous alloys. In this analysis, two cases will be considered:

a) standard die cavity preparation in which die cavity inserts are prepared by electro-discharge machining (EDM), and

b) investment casting and finish machining of die cavity inserts. It will be shown that significant savings may be realized by investment cast-

ing die cavity inserts to shape when both types of die fabrication yield similar die lives.

For both cases, the shot sleeve, plunger tip and runner pads are fabricated in H-13 tool steel at a cost of $400, $80, and $1000, respectively. Die life is estimated at 10,000 shots, at which time each item is replaced.

For the first case, EDM preparation of die inserts, metal cost for 16 cavity insert sets is estimated at $600 ($4/pound for Elbrodur RS copper alloy in wrought form). Initial tooling for a 16 cavity set by electro-discharge machining has been quoted at $22,000. Die life has again been estimated at 10,000 shots, at which time insert sets are reworked to a depth of 1/16" by EDM and shimmed from behind at a cost of $10,400. It is estimated that die cavity inserts may be reworked in this manner 9 times. Total machine component costs, including costs for an H-13 shot sleeve, plunger tip and runner pads amortized over 10,000 shots, and 16 Elbrodur RS die cavity insert sets amortized over 100,000 shots, would be $1.310/shot.

In the second case, investment casting and finishing of die cavity inserts, significant savings may be realized if a similar 10,000 shot die life is assumed. An initial cost of $2,000 for preparation of a tool steel master hobb from which wax preforms for the investment casting process may be made is included as a capital investment. Insert sets are investment cast in Elbrodur RS at a cost of $200/set, including metal costs and finishing costs. In this manner, total machine component costs, including costs for a H-13 shot sleeve, plunger tip and runner pads,

amortized over 10,000 shots, is reduced to $0.4680/shot.

A total cost breakdown for machine casting the M-85 by the Thixocast process using EDM prepared copper die cavity inserts is given in Table 6 and Table 8. A final casting cost of 15.38¢/casting is possible using this technique, with over one-half (56.03%) of the total cost representing machine component costs.

Tables 7 and 9 present a cost breakdown for machine casting the same part by the Thixocast process utilizing investment cast copper die cavity inserts. A significant reduction in costs is realized, provided similar die lives are possible. A final casting cost of 9.84¢/casting is possible by this technique, with approximately one-third (31.28%) of the total cost representing machine component costs.

V. DISCUSSION

The purpose of this study has been to determine the feasibility of machine casting low alloy steel by the Thixocast process. The major effort has been directed at investigating machine component wear, especially die wear, and its effect on the overall process economics.

The Thixocast process for low alloy steel involves two major innovations which separate it from standard die casting practice. The first, from whence the name is derived, involves the machine casting of metal in the semi-solid state. Casting soundness is improved over conventional liquid metal die casting techniques due to the entrapment of less air during the filling and to a reduction of solidification shrinkage in the dies. In addition, the reduction of the actual casting temperature to the mid liquid-solid range, together with the large reduction in the heat content of a semi-solid metal, owing to the fact that over half the heat of fusion has been removed prior to casting, combine to reduce die thermal shock and consequently extend die lives to the point where ferrous machine casting appears to be economically viable.

The second innovation involves the use of copper alloy die materials which are directly water spray quenched after casting ejection to maintain operating temperature at approximately 50°C. Standard die casting practice has utilized tool die steels (H-13 or H-21) or other exotic materials (TZM molybdenum base alloy) as either entire die assemblies or as die inserts. Operating the dies at high temperatures (> 400°C) reduces

thermal shock during injection, and improves die filling. However, the flow behavior of Thixocast metal is such that cold dies can be used and still achieve good casting filling and soundness while maintaining adequate die life to making the process economically viable.

The study of 2200 shots conducted in this work indicates that cold Elbrodur RS dies are far superior to the standard tool steel die materials (H-13 and H-21) in their ability to withstand thermal fatigue during ferrous die casting. Ultimate die life is difficult to estimate, and will be sensitive to cavity configuration and casting size. However, a life on the order of 10,000 shots appears to be reasonable.

This life may seem low when compared to standard aluminum die casting practice, where die lives of a hundred thousand or more shots are quoted. However, aluminum casting temperatures are on the order of 600°C, while ferrous casting temperatures are over twice that high, on the order of 1500°C, and will obviously have a more pronounced effect on die thermal fatigue.

Photographs of TZM die inserts used by GKN Ferro-Di[24] reveal gross heat checking after 10,000 shots of liquid stainless steel. Differences in the cavity configurations and the total shots that the TZM inserts and Elbrodur RS inserts have been exposed to make direct comparisons of the two materials impossible. However, extrapolation of the die wear data recorded in this study, both parting line erosion and heat checking crack growth, indicate the Elbrodur RS dies in conjunction with Rheo-

cast metal would compare very favorably with TZM alloy dies and liquid metal. The copper alloy dies, of course, are very much less expensive. In addition, the use of Rheocast metal eliminates shot sleeve warpage as a problem area in ferrous machine casting. Reduction of the charge metal-to-shot sleeve contact area because of Rheocast metals thixotropic nature could be instrumental in extending machine casting techniques to ferrous alloys.

The economic analysis conducted in this work, using a specific small AISI 4340 part indicates that the Thixocast process is an economically viable large production part forming process. Using EDM prepared die cavities, and assuming a die life of 10,000 shots before reworking, a manufacturing cost of 15.38¢/casting has been calculated, as compared to an approximate manufacturing cost by investment casting of 16¢/casting.

Furthermore, Elbrodur RS is a readily castable alloy (much more so than the standard tool die steels which have met limited acceptance as die components in the investment cast form). The use of investment cast Elbrodur RS die inserts to machine cast ferrous parts improves the economics markedly, provided similar die life is possible. A sixteen-cavity die set for the M-85 pawl can be prepared for $3,200 by investment casting, as opposed to $22,000 for EDM tooling, and this yields a Thixocasting manufacturing cost of only 9.84¢ per casting, a significant reduction over that achievable by other casting methods.

VI. CONCLUSIONS

1. Approximately 2000 pounds of Rheocast AISI 4340 was successfully produced in a high temperature continuous Rheocaster. Design, control methods, and operation of the Rheocaster are described in detail.

2. The viscosity of Rheocast AISI 4340 slurry increases with increasing fraction solid. The viscosity of a slurry containing a given fraction solid increases with increasing solidification rate and decreasing shear rate. Solidification rate and shear rate have a greater effect on slurry viscosity at high fractions solid than at low fractions solid.

3. The effective primary solid particle size in a Rheocast AISI 4340 slurry increases with increasing fraction solid. The effective primary solid particle size in a slurry containing a given fraction solid decreases with increasing shear rate up to a shear rate of 900 sec^{-1}. Shear rate has a greater effect on particle size at high fractions solid than at low fractions solid. Large primary solid particle sizes are associated with high viscosity slurries.

4. Rheological behavior of Rheocast AISI 4340 is qualitatively similar to that of other previously studied (e.g., tin-lead, copper, aluminum, and other ferrous alloys).

5. 2,200 small ($\sim$ 1 oz.) AISI 4340 parts were successfully machine cast by the Thixocast process using surface quenched copper dies operating at $\sim$50°C.

6. Casting trials of 2200 shots indicate that Elbrodur RS copper alloy dies are far superior to standard tool steel die materials (H-13 and H-21) for Thixocasting ferrous alloys. Parting line erosion and some cracking on internal die radii are the two modes of die deterioration. Cracking is sensitive to die configuration, and including a radius on die cavity corners will reduce susceptibility to die

cracking. Based on the condition of the die cavity insert set after 2,200 shots, die life has been estimated at 10,000 shots.

7. AISI 4340 Thixocastings produced in surface quenched copper dies experience very rapid cooling during solidification (> 10^4°C/sec). A uniform distribution of irregularly shaped primary solid particles are dispersed in a rapidly quenched liquid matrix. The quenched liquid matrix is generally harder than primary solid particles.

8. No shot sleeve warpage was encountered when machine casting low alloy steel by the Thixocast process.

9. A manufacturing cost analysis indicates that 10,000 shots in Elbrodur RS copper alloy dies prepared by electrodischarge machining is adequate to make the Thixocast process for low alloy steel economically viable. Approximately one-half of the casting cost for an individual part is for machine components. The majority of that cost represents EDM preparation of die cavities. Manufacturing costs for relatively simple shaped, one ounce Thixocastings would be approximately 15¢ per casting when dies are prepared by EDM.

10. Elbrodur RS is an easily cast alloy (much more so than the conventional tool die steel such as H-13 and H-21), and significant economic advantages are possible by employing investment casting to shape die cavity insert, provided adequate die life on the order of 10,000 shots is possible. A cost analysis for Thixocasting one ounce ferrous parts in investment cast die inserts indicates that manufacturing costs would be approximately 10¢ per casting with a 10,000 shot die life. This cost would be highly competitive with existing forming processes for ferrous alloys.

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TABLE 1

Results of rotor drive amperage-viscosity correlation experiments

Viscosity Standard #	Rotation Speed (RPM)	Rotor Drive Amperage	T (°C)	η (poise)	RPM $\cdot$ η
S600	400	0.1	35.0	6.0	2,400
S600	400	0.1	33.0	7.0	2,800
S600	400	0.2	25.0	12.5	5,000
S2000	400	0.3	35.5	20.0	8,000
S2000	400	1.4	20.0	71.0	28,400
S600	600	0.2	33.3	6.9	4,140
S600	600	0.2	30.3	8.5	5,100
S600	600	0.2	26.0	11.5	6,900
S2000	600	0.4	35.5	20.0	12,000
S2000	600	1.2	24.0	49.0	29,400
S600	800	0.1	42.0	4.6	3,680
S600	800	0.2	33.8	6.6	5,280

TABLE 1 (continued)

Results of rotor drive amperage-viscosity correlation experiments

Viscosity Standard #	Rotation Speed (RPM)	Rotor Drive Amperage	T (°C)	η (poise)	RPM $\cdot\ \eta$
S600	800	0.3	30.0	8.7	6,960
S600	800	0.5	26.0	11.5	9,200
S2000	800	0.6	35.5	20.0	16,000
S2000	800	1.1	28.0	36.0	28,800
S600	1000	0.2	42.0	4.6	4,600
S600	1000	0.4	34.3	6.4	6,400
S600	1000	0.5	28.0	10.0	10,000
S600	1000	0.6	25.0	12.5	12,500
S2000	1000	0.9	34.0	23.0	23,000
S2000	1000	1.0	32.0	27.0	27,000

TABLE 2

Compositions of AISI 4340 feed stock, Rheocast 4340 water-quenched samples, and Thixocast 4340

	Feed Stock as Received	Water Quench Number 13-3	Water Quench Number 13-51	Thixocasting Number 12-4	AISI 4340 Specifications
wt. % Carbon	0.41	0.40	0.43	0.43	0.38-0.43
wt. % Manganese	0.70	0.67	0.77	0.63	0.60-0.80
wt. % Phosphorous	0.005	0.005	0.005	0.005	0.035 max
wt. % Sulfur	0.020	0.013	0.012	0.011	0.040 max
wt. % Silicon	0.20	0.31	0.33	0.34	0.20-0.35
wt. % Nickel	1.76	1.81	1.65	1.70	1.65-2.00
wt. % Chromium	0.75	0.76	0.75	0.75	0.70-0.90
wt. % Molybdenum	0.23	0.28	0.22	0.21	0.20-0.30

TABLE 3

Phase micro-hardness of primary solid particles and prior liquid matrix in 4340 Rheocast water quenches, air-cooled Thixocastings and vermiculite cooled Thixocastings

	Primary Solid Particles		Prior Liquid Matrix	
	Knoop Hardness Number	Rockwell C Conversion	Knoop Hardness Number	Rockwell C Conversion
Rheocast water quenched structure	542	50	780	62
Thixocast air cooled structure	331	33	741	60
Thixocast vermiculite cooled structure	270	24	458	44

TABLE 4

Capital Equipment Costs for Proposed Rheocasting System

	Purchase Price ($)	Write-off Period (years)	Annual Depreciation ($/year)
2 100 KW induction power supplies	100,000	15	6,700
2 500-pound melting units	10,000	10	1,000
4 20 KW induction power supplies	60,000	15	4,000
2 Rheocasters	40,000	10	4,000
Billet casting system	20,000	10	2,000
Instrumentation	10,000	10	1,000
Totals:	$240,000		$18,700

TABLE 5

Total Manufacturing Cost Breakdown
For Production of Rheocast AISI 4340

	Cost ($/lb)
Capital Equipment	0.008
Furnace Materials	0.013
Expendable Materials	0.008
Labor	0.115
Base Metal	0.274
Melting	0.023
Total:	$0.441/lb

TABLE 6

Capital Equipment Costs for Machine Casting the M-85 Pawl Cartridge Stop by the Thixocast Process Using EDM Prepared Elbrodur RS Die Cavity Inserts

	Purchase Price ($)	Write-off Period (years)	Annual Depreciation ($/year)
50 KW induction power supply	26,000	15	1,733.33
400 ton cold chamber die casting machine	50,000	12	4,166.67
2 fully prepared mold bases ($1,000 purchase price, $8,000 tooling)	18,000	15	1,200.00
automatic mold wiping system (including die stripping, water spray quenching, lubricating and drying)	10,000	10	1,000.00
reheating station (including continuous feed tube furnace and controls)	10,000	10	1,000.00

Total Annual Capital Equipment Costs = $9,100/year

TABLE 7

Capital Equipment Costs for Machine Casting the M-85 Pawl, Cartridge Stop by the Thixocast Process Using Investment Cast and Finished Machined Elbrodur RS Die Cavity Inserts

	Purchase Price ($)	Write-off Period (years)	Annual Depreciation ($/year)
50 KW induction power supply	26,000	15	$1,733^{\underline{33}}$
400 ton cold chamber die casting machine	50,000	12	$4,166^{\underline{67}}$
2 fully prepared mold bases ($1,000 purchase price, $8,000 tooling)	18,000	15	$1,200^{\underline{00}}$
automatic mold wiping system (including die stripping, water spray quenching, lubricating and drying)	10,000	10	$1,000^{\underline{00}}$
reheating station (including continuous feed tube furnace and controls)	10,000	10	$1,000^{\underline{00}}$
hobb (tool steel master for investment casting die cavity inserts)	2,000	10	$200^{\underline{00}}$

Total Annual Capital Equipment Costs = $9,300/year

TABLE 8

Total Manufacturing Cost Breakdown for
Thixocast M-85 Pawl*

	($/year)	($/shot)	Percent of total manufacturing cost
Capital Equipment	9,100	0.0152	0.65%
Additional Materials	1,000	0.0017	0.07%
Labor	105,000	0.1750	7.49%
Expendable Materials	-	0.10	4.28%
Reheating Energy	-	0.01	0.43%
Rheocast Metal	-	0.726	31.05%
Machine Components	-	1.310	56.03%
		$2.3379/shot	

Utilizing a 16 cavity mold and assuming a 95% casting efficiency:

Individual Part Manufacturing Cost = $0.1538/casting

* Machine casting cartridge stop using EDM prepared Elbrodur RS die cavity inserts. Annual production per machine is assumed to be 600,000 shots. Expected machine component lives are estimated at 10,000 shots.

TABLE 9

Total Manufacturing Cost Breakdown for
Thixocast M-85 Pawl*
(Elbrodur RS)

	($/year)	($/shot)	Percent of total manufacturing cost
Capital Equipment	9,300	0.0155	1.04%
Additional Materials	1,000	0.0017	0.11%
Labor	105,000	0.1750	11.70%
Expendable Materials	-	0.10	6.68%
Reheating Energy	-	0.01	0.67%
Rheocast Metal	-	0.726	48.62%
Machine Components	-	0.4680	31.28%
		$1.4962/shot	

Utilizing a 16 cavity mold and assuming a 95% casting efficiency:

Individual Part Manufacturing Cost = $0.0984/casting

* Machine casting cartridge stop using investment cast and finish machined Elbrodur RS die cavity inserts. Annual production per machine is assumed to be 600,000 shots. Expected machine component lives are estimated at 10,000 shots.

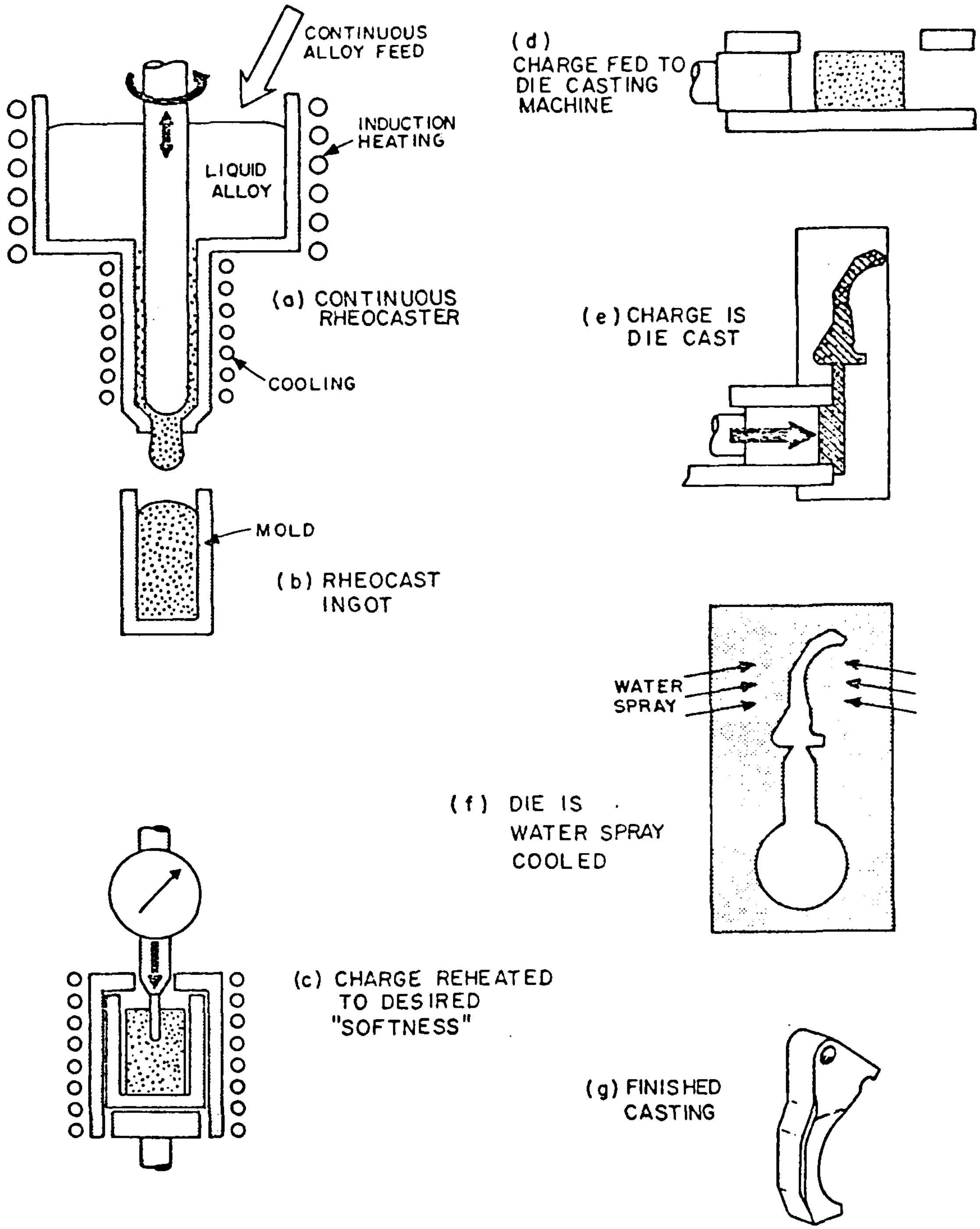
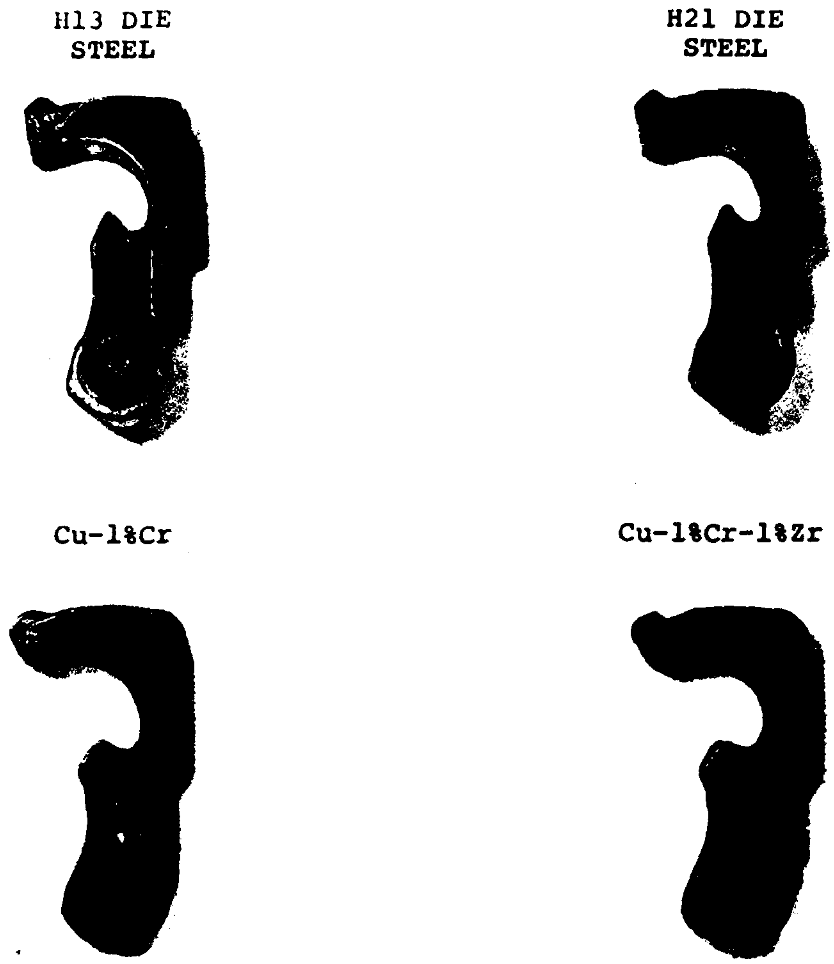


Figure 1. Schematic diagram of the Thixocast process for machine casting low alloy steel components.



FIVE HUNDREDTH SHOT OF THE ACTUAL (304 STAINLESS) OR SIMULATED (440C STAINLESS) M16 RIFLE HAMMER CAST IN VARIOUS DIE MATERIALS

Figure 2. The 500th Thixocastings produced in H-13 die steel, H-21 die steel, Cu-0.8% Cr dies, and Elbrodur RS (Cu-1% Cr-1% Zr) dies. From Ref. 6.

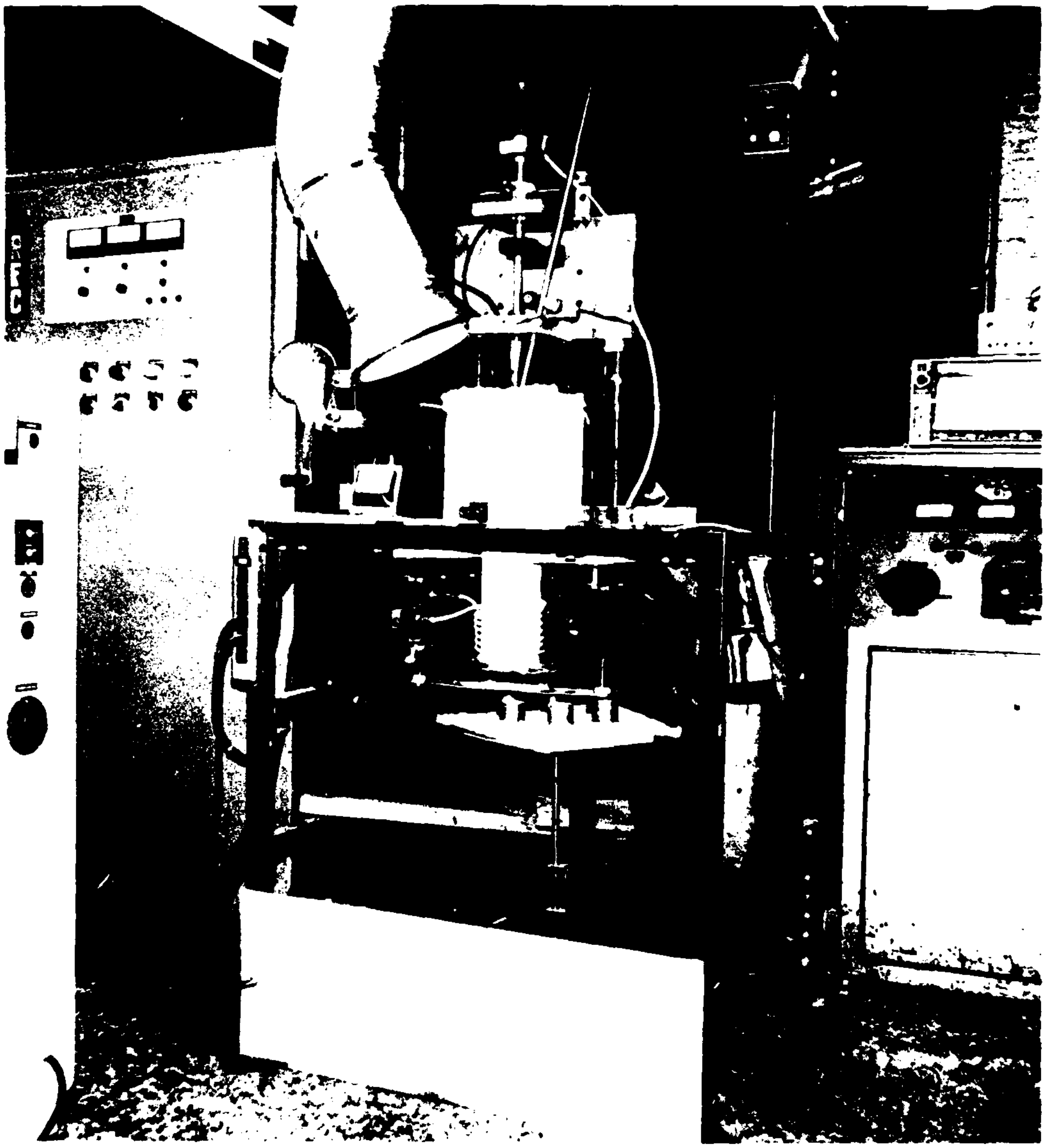


Figure 3. The high temperature continuous Rheocaster set up for continuous production of AISI 4340.

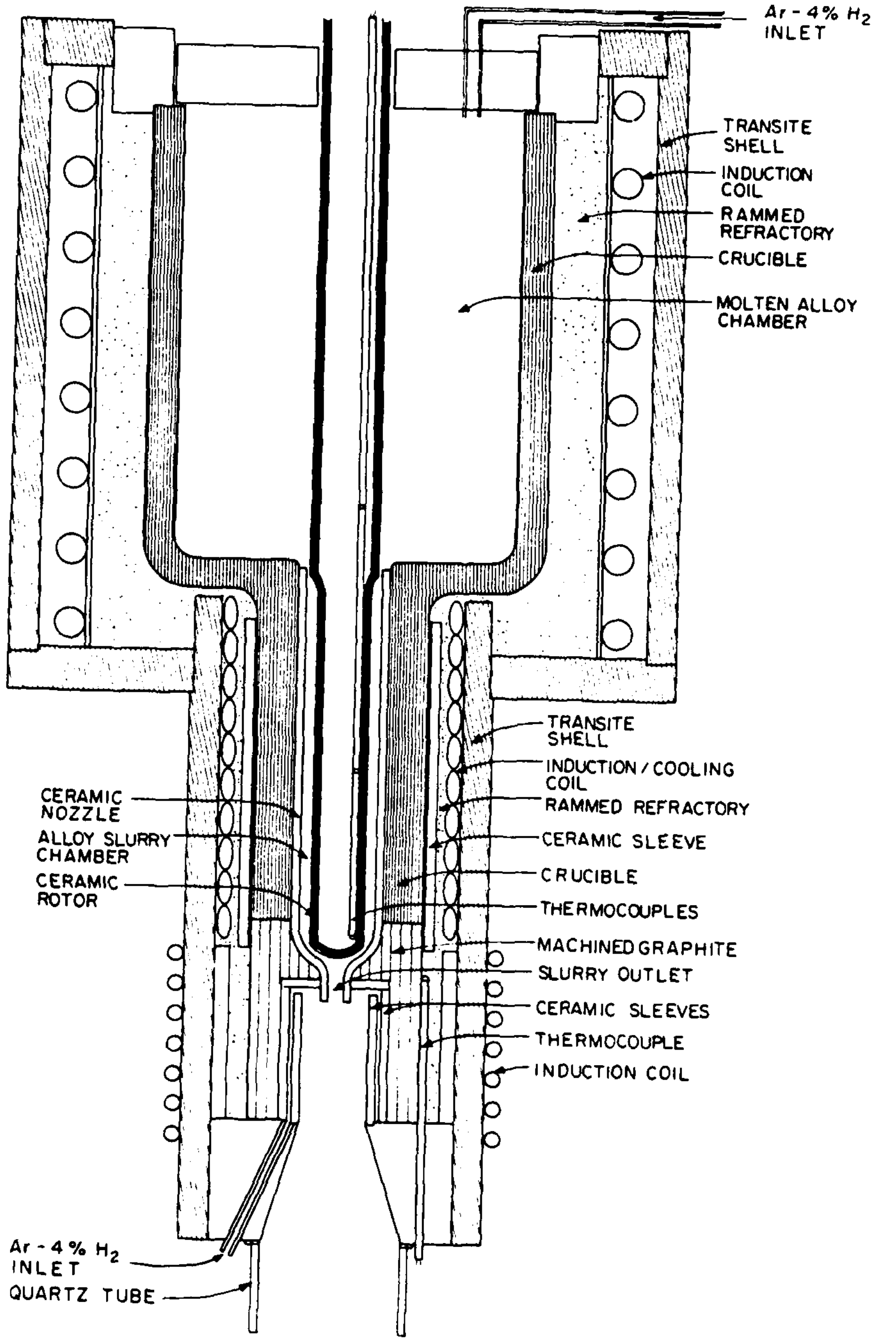


Figure 4. Schematic cross-section of the high temperature continuous Rheocaster.

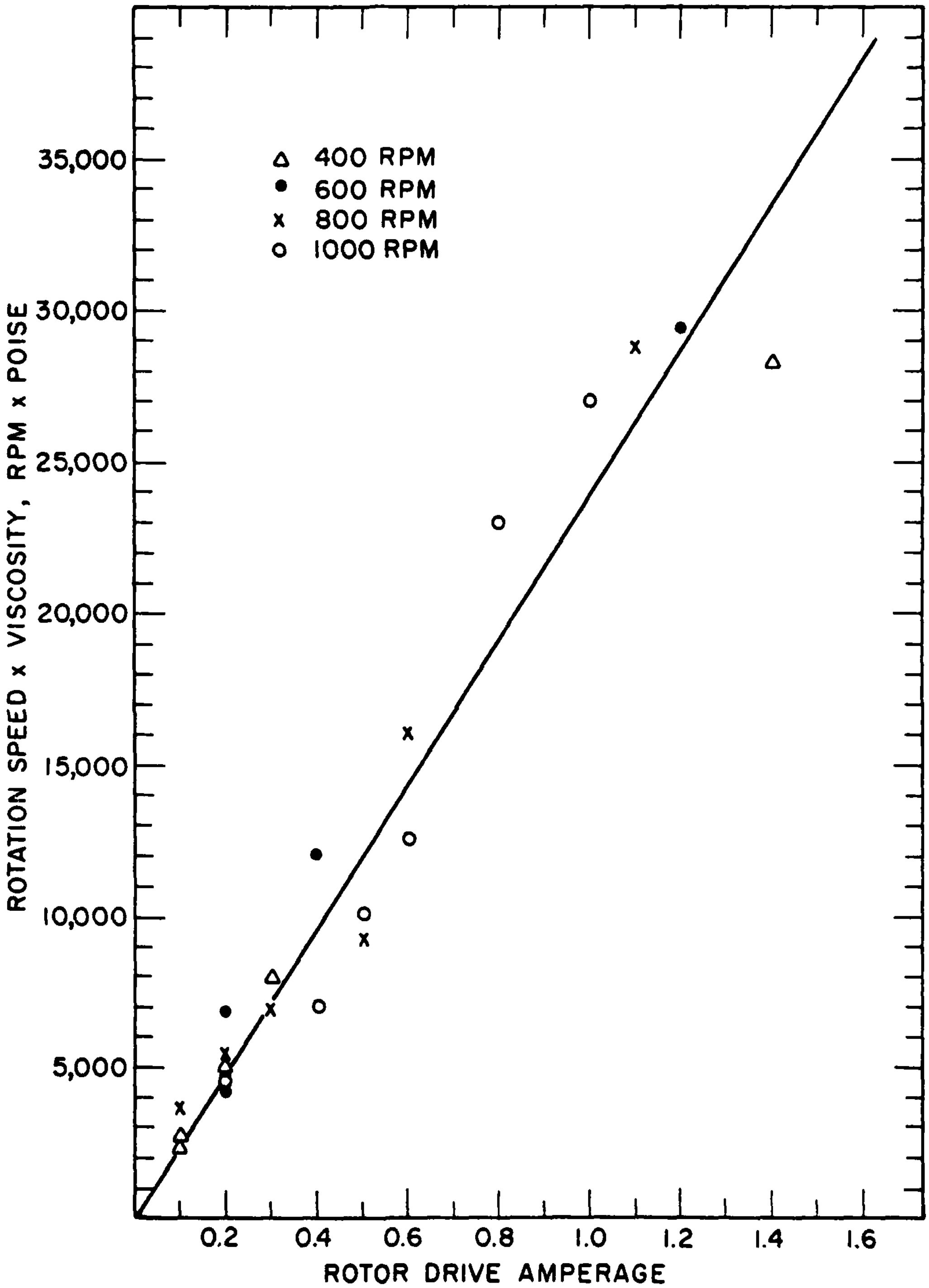
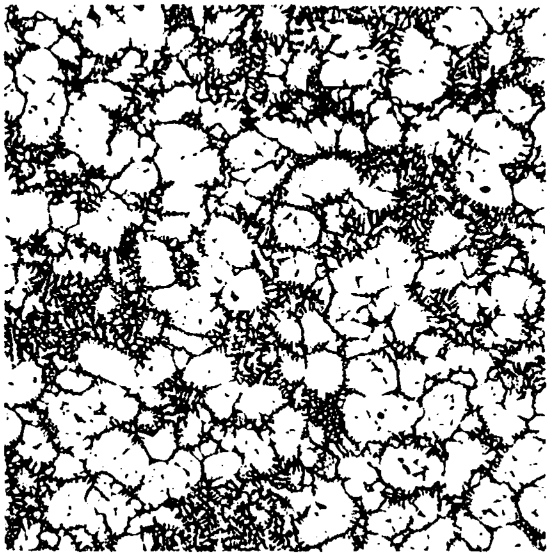
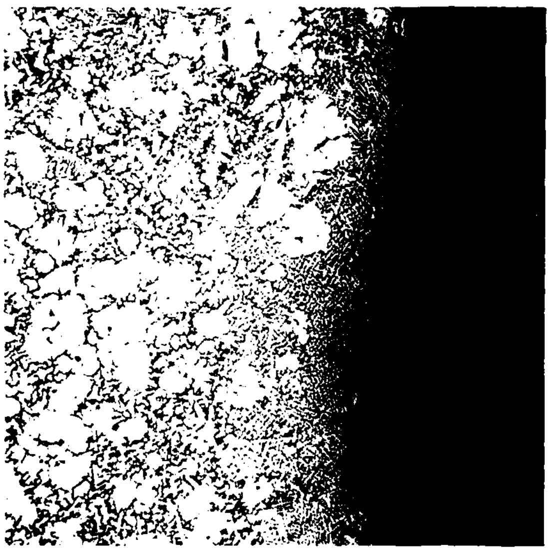


Figure 5. Experimental calibration curve for converting rotor drive amperage at a given rotation speed to mean fluid viscosity.



(a)



(b)

Figure 6. Microstructures of water quenched samples of Rheocast AISI 4340, showing (a) interior of sample, and (b) edge of sample with low fraction solid layer. 25.6X.

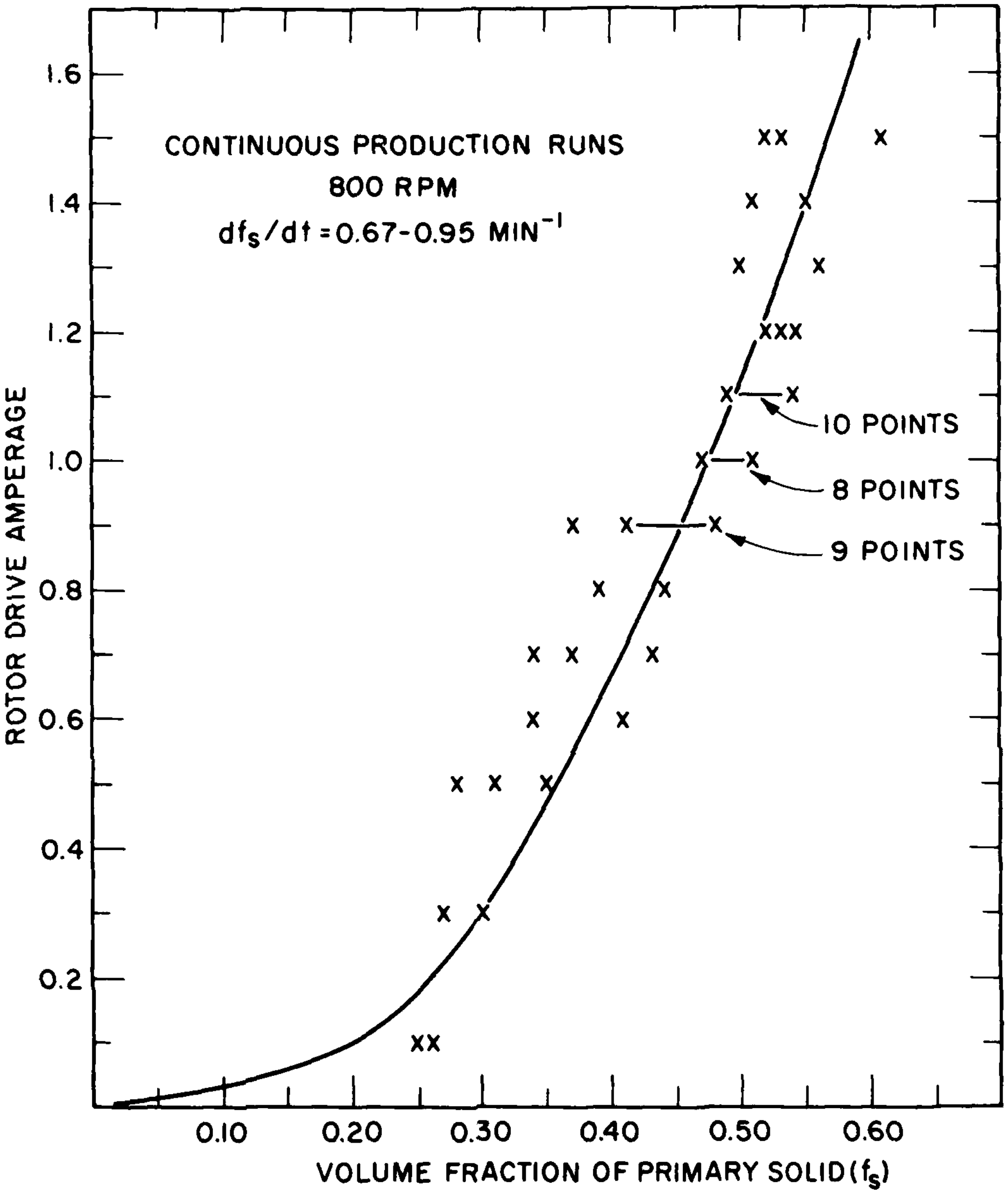


Figure 7. Effect of volume fraction of primary solid on the amperage required to drive the rotor at 800 RPM in Rheocast 4340. Data from continuous production runs with solidification rates ranging from 0.67 min^{-1} to 0.95 min^{-1}.

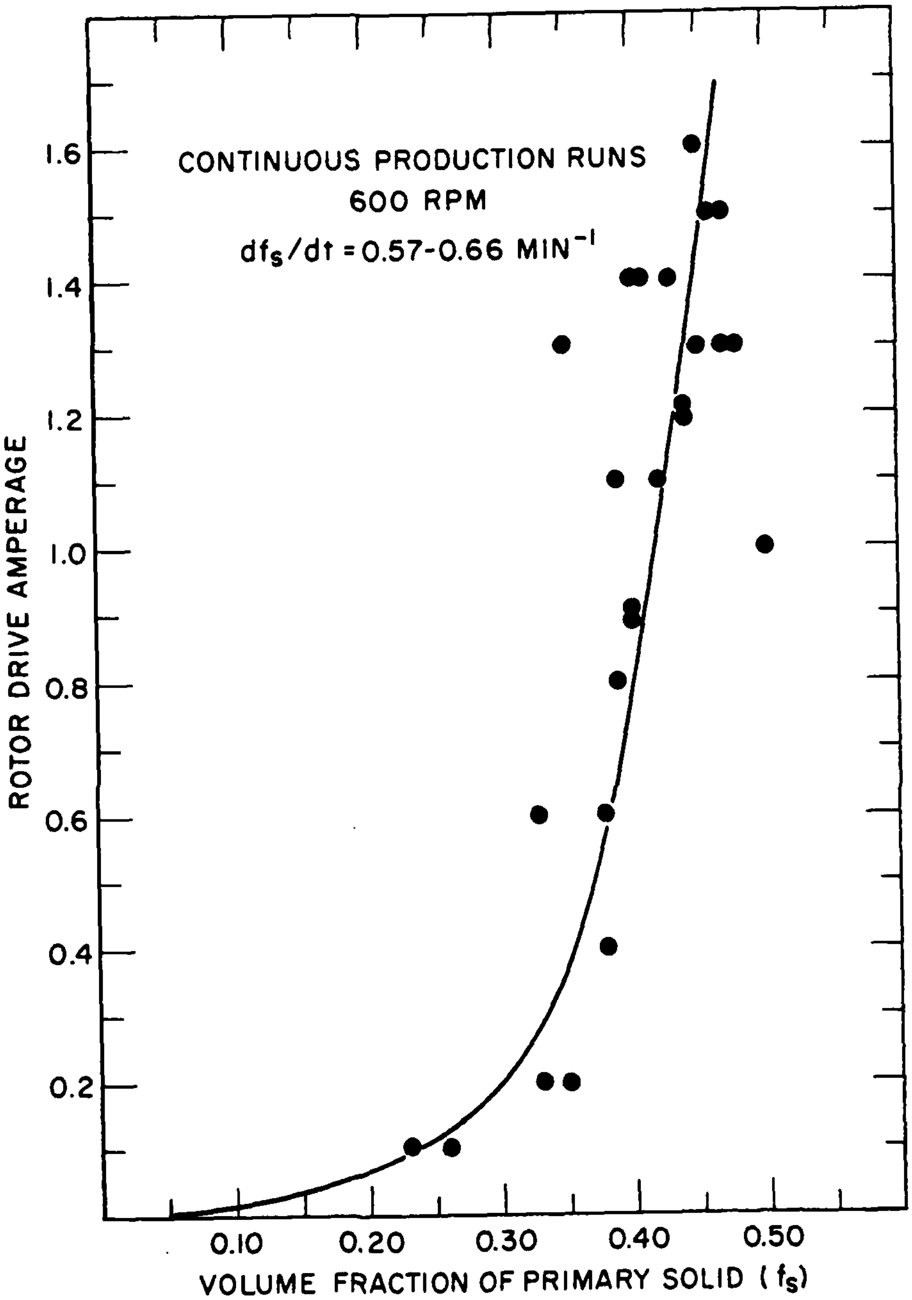


Figure 8. Effect of volume fraction of primary solid on the amperage required to drive the rotor at 600 RPM in Rheocast 4340. Data from continuous production runs with solidification rates ranging from 0.57 min^{-1} to 0.66 min^{-1}.

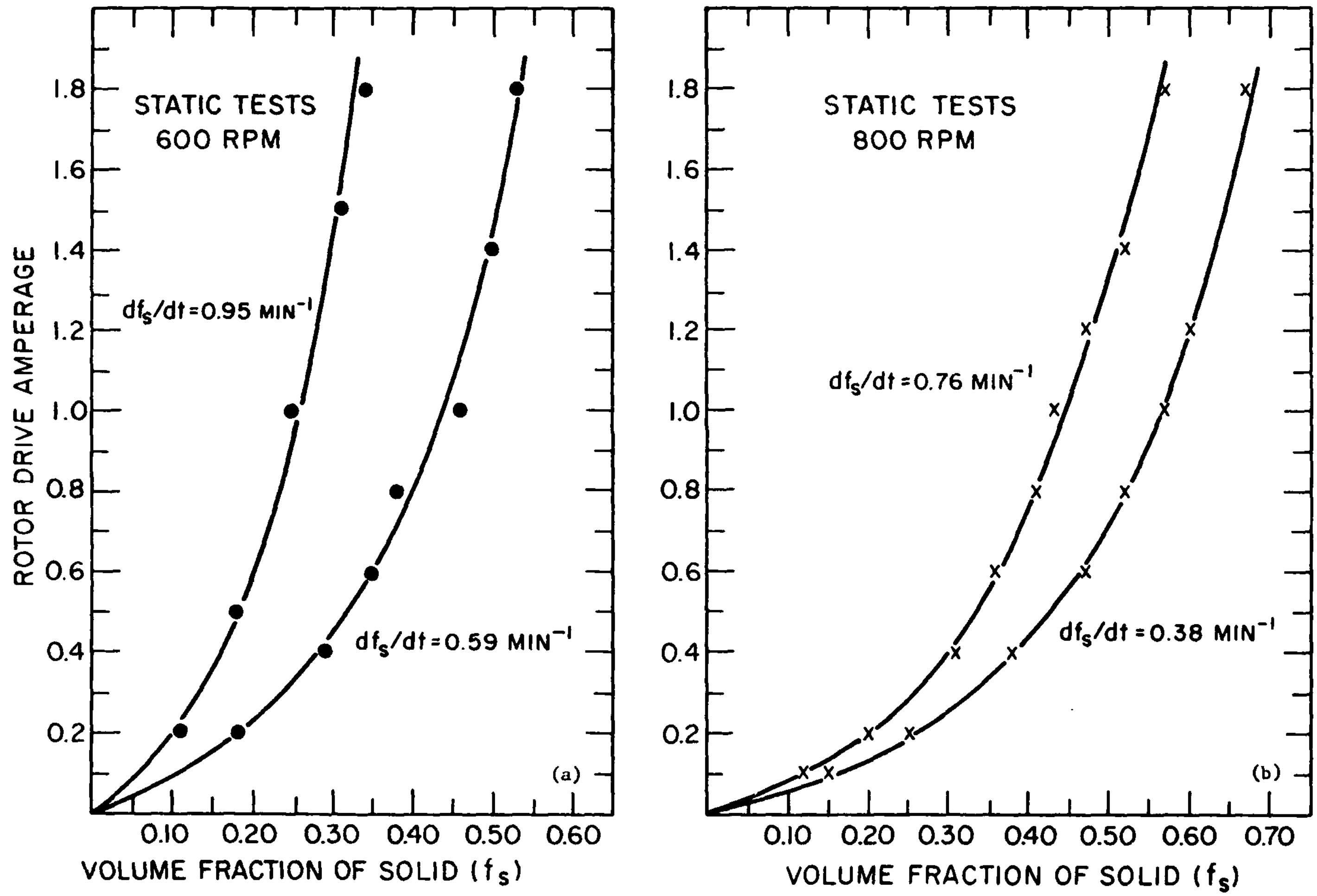


Figure 9. Effect of volume fraction of primary solid on the amperage required to drive the rotor at constant speed in Rheocast 4340. Data from static tests run at (a) 600 RPM with solidification rates of 0.95 min^{-1} and 0.59 min^{-1}, and (b) 800 RPM with solidification rates of 0.76 min^{-1} and 0.38 min^{-1}.

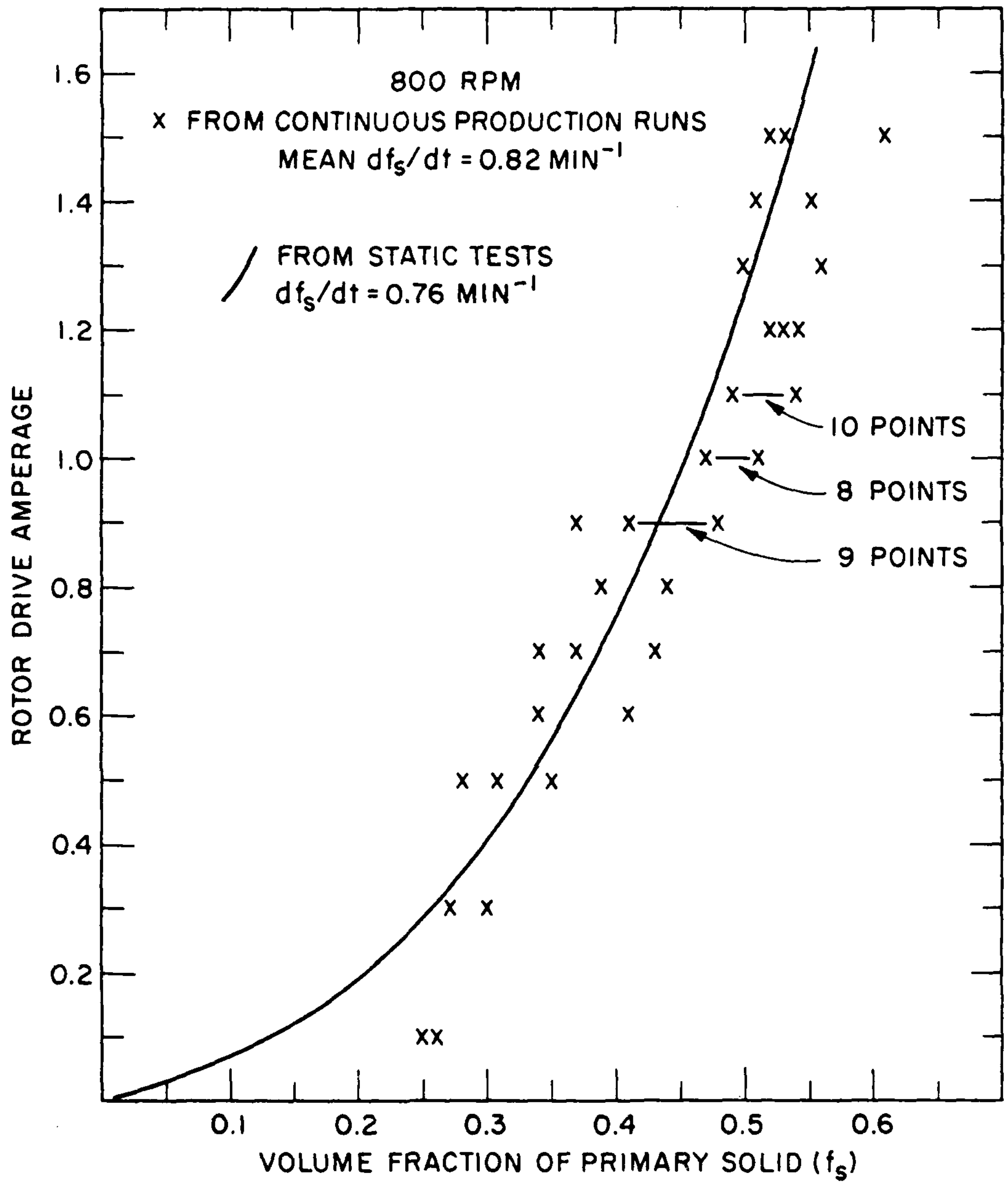


Figure 10. Comparison of the results of continuous production runs and static tests with equivalent solidification rates on the effect of fraction solid on the amperage required to drive the rotor at 800 RPM in Rheocast 4340.

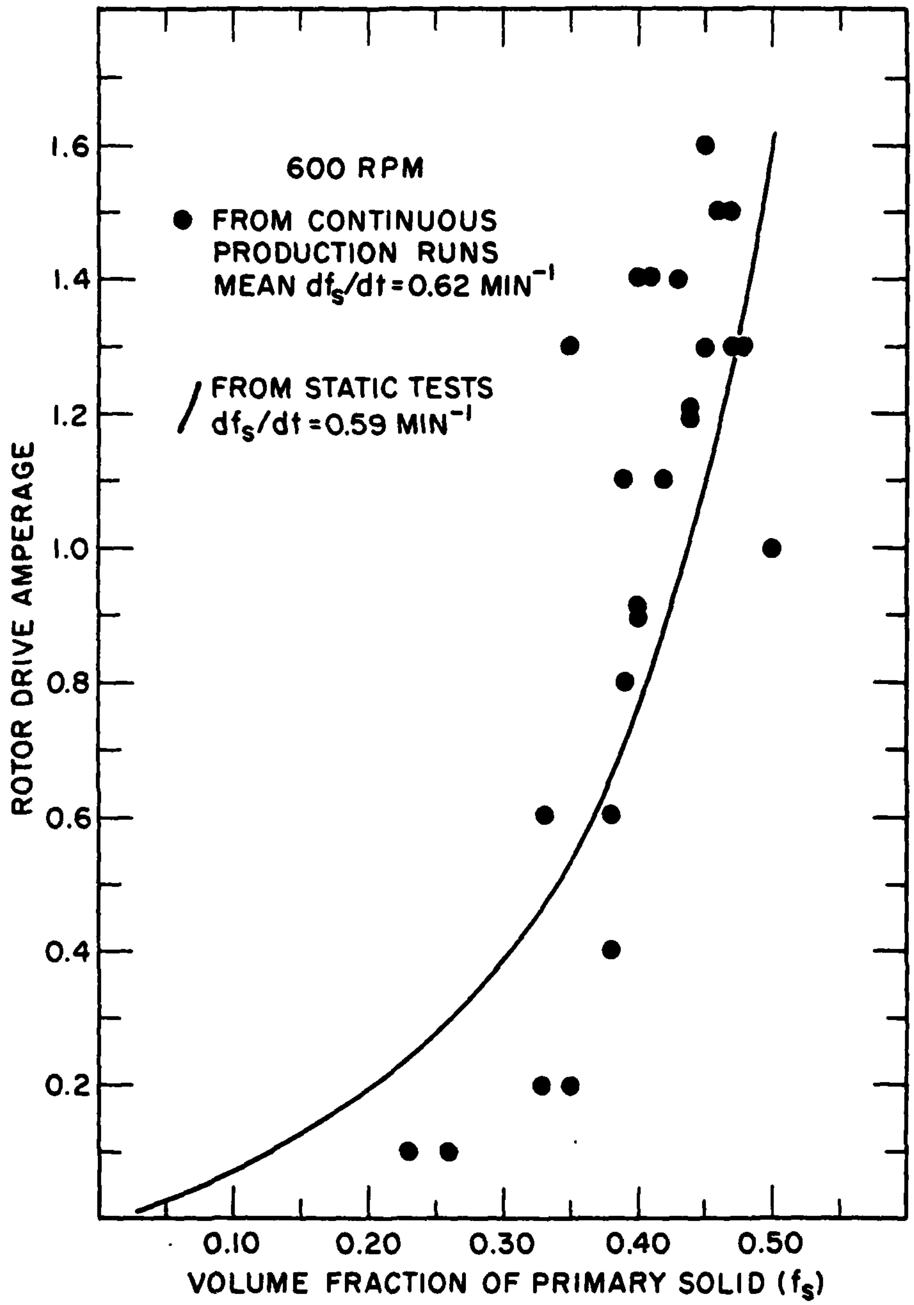


Figure 11. Comparison of the results of continuous production runs and static tests with equivalent solidification rates on the effect of fraction solid on the amperage required to drive the rotor at 600RPM in Rheocast 4340.

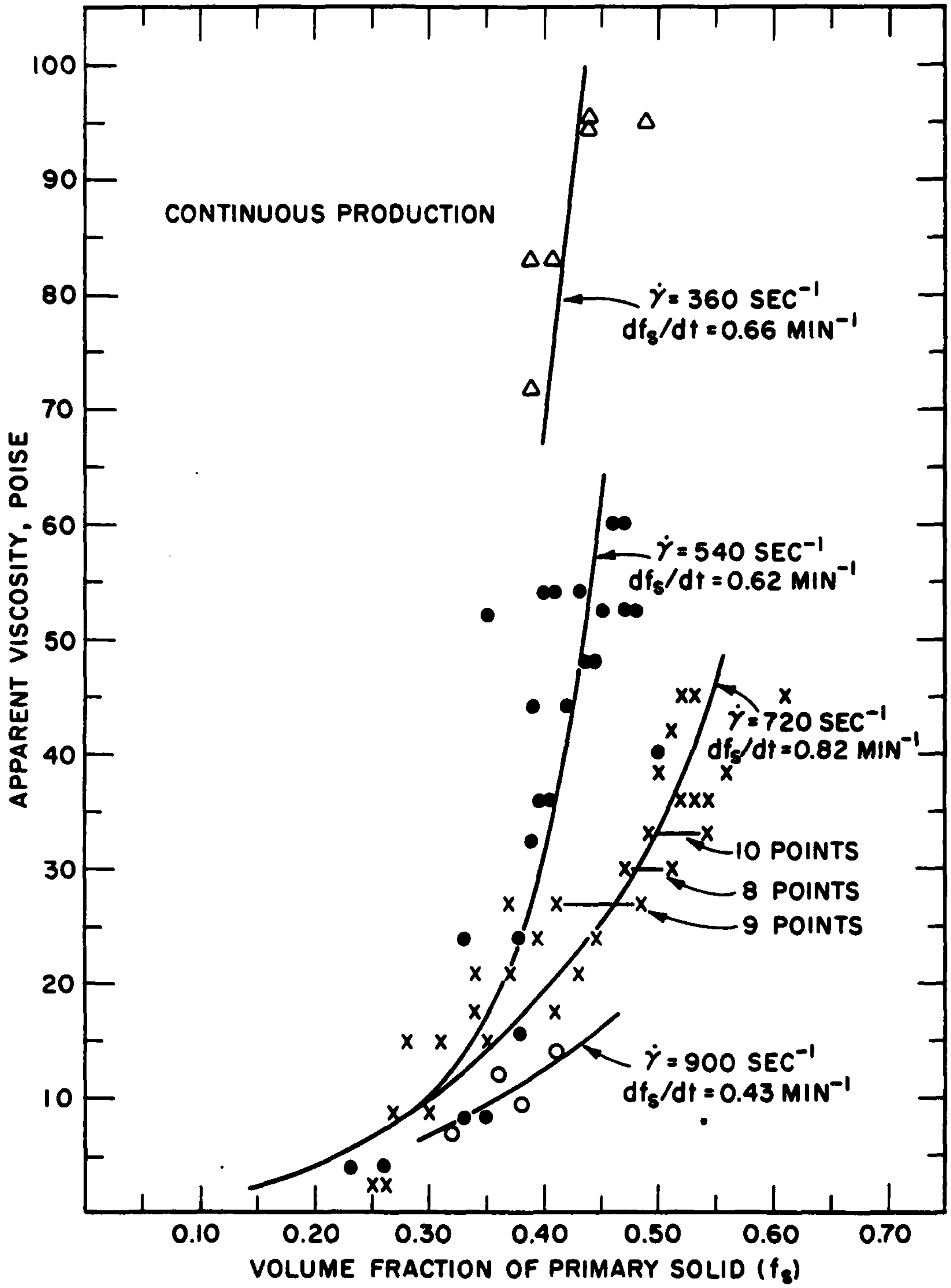


Figure 12. Effect of volume fraction of primary solid on the apparent viscosity of Rheocast 4340. Effect of shear rates equal to 360, 540, 720 and 900 sec^{-1}. Data taken from continuous production runs.

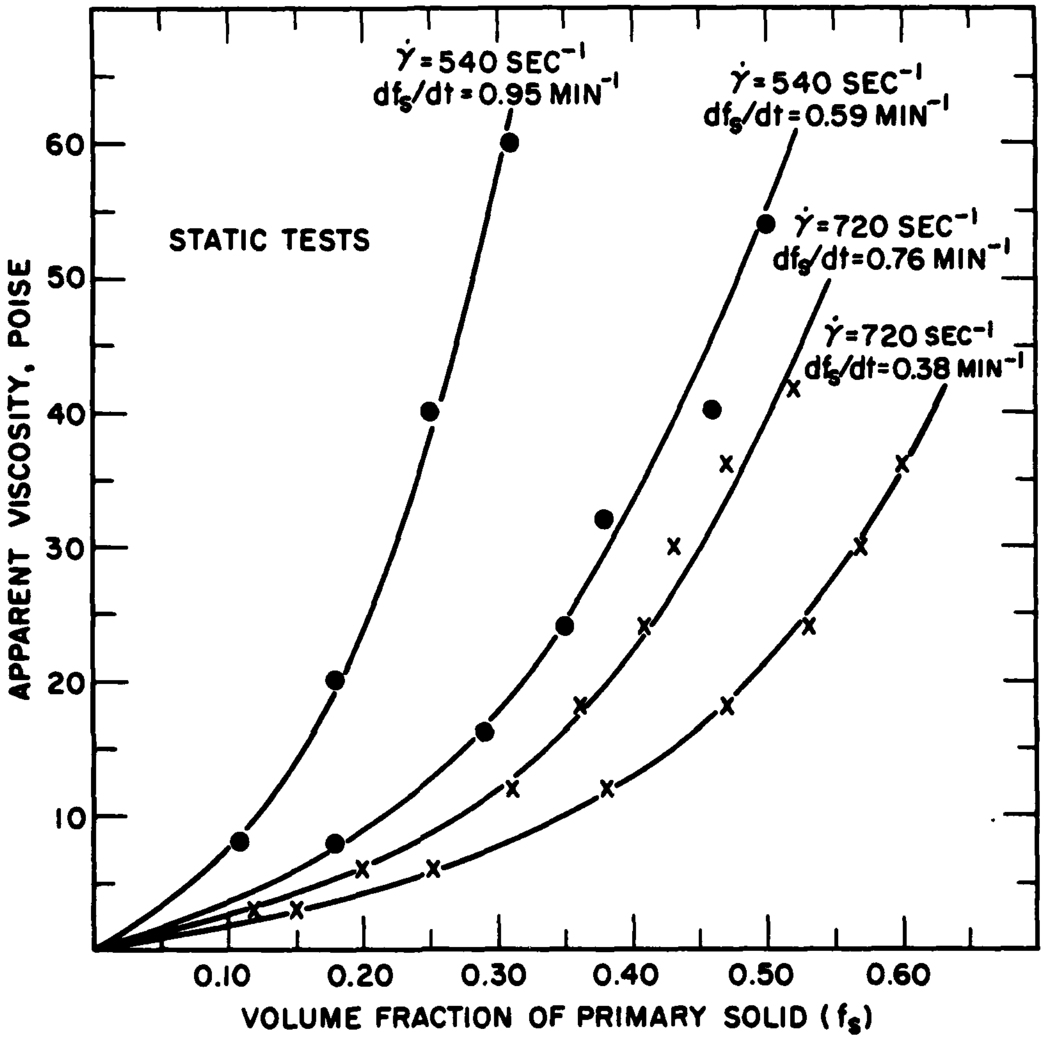


Figure 13. Effect of volume fraction of primary solid on the apparent viscosity of Rheocast 4340. Effect of two shear rates, 540 and 720 sec^{-1} at two different solidification rates each, 0.95 min^{-1} and 0.59 min^{-1}, and 0.76 min^{-1} and 0.38 min^{-1}, respectively. Data taken from static tests.

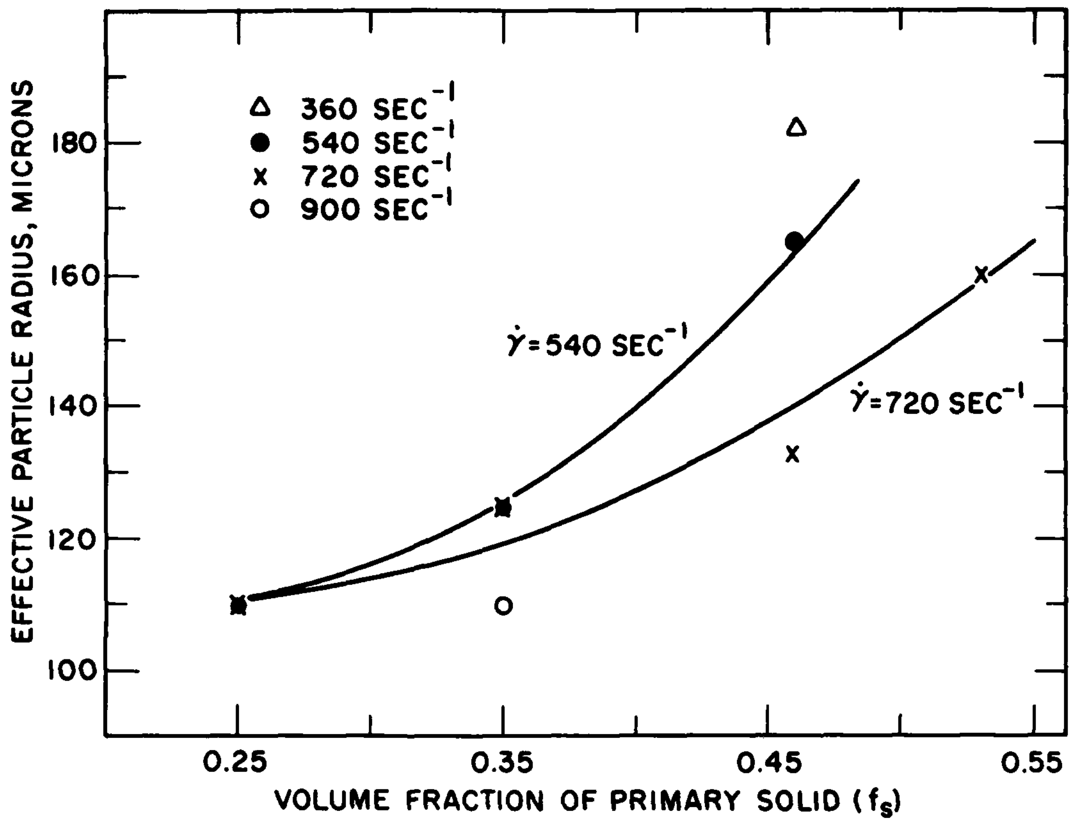


Figure 14. Effect of volume fraction of primary solid on the effective primary solid particle radius in Rheocast 4340. Effect of shear rates equal to 360, 540, 720 and 900 sec^{-1}.

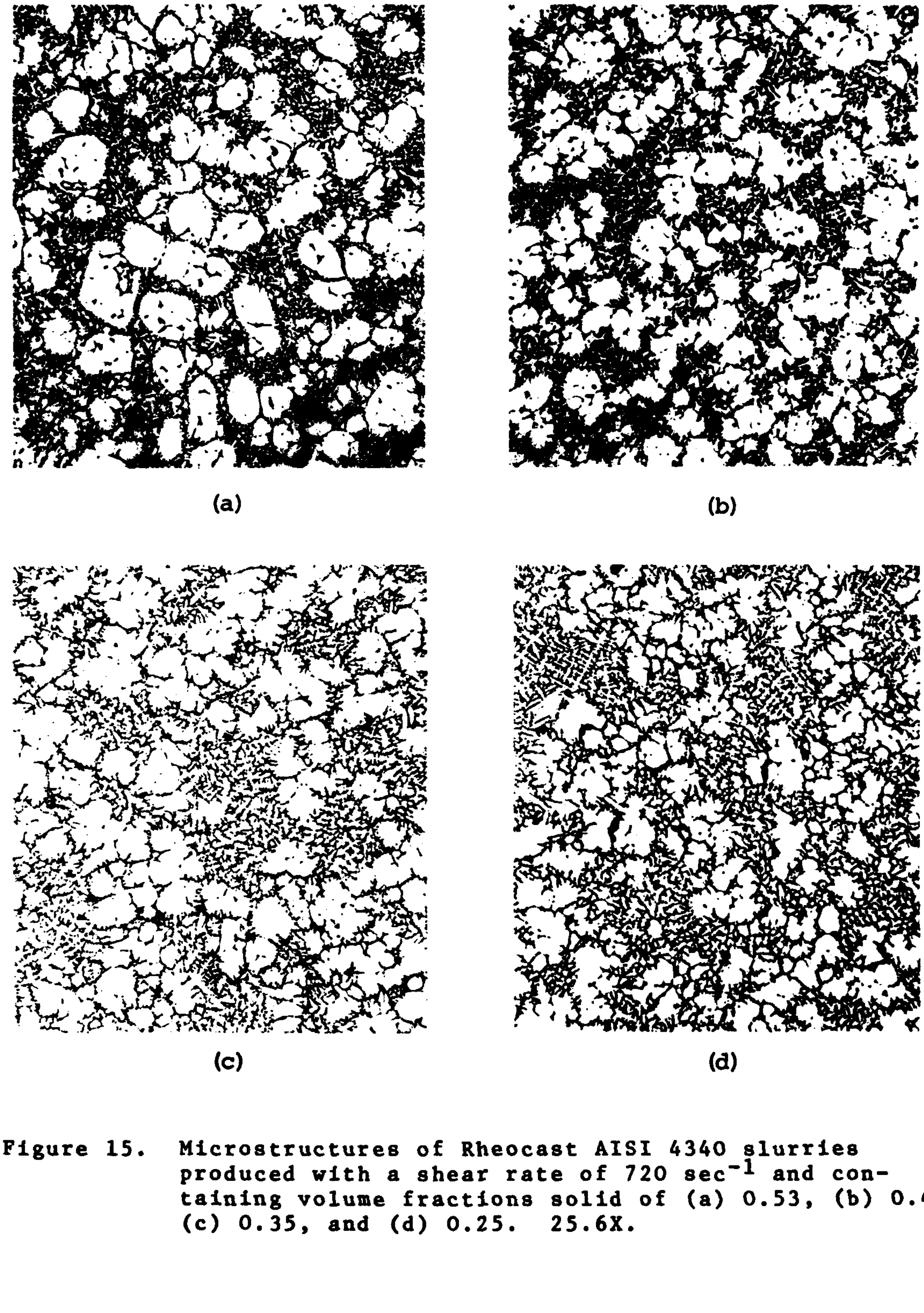


Figure 15. Microstructures of Rheocast AISI 4340 slurries produced with a shear rate of 720 sec^{-1} and containing volume fractions solid of (a) 0.53, (b) 0.46, (c) 0.35, and (d) 0.25. 25.6X.

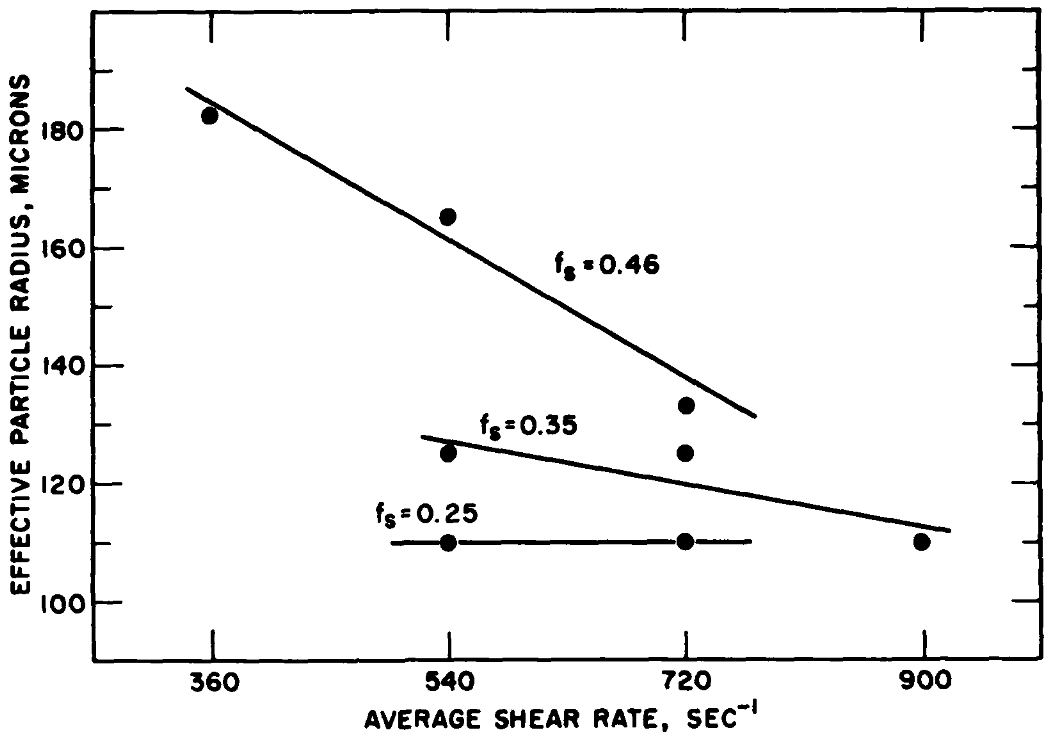
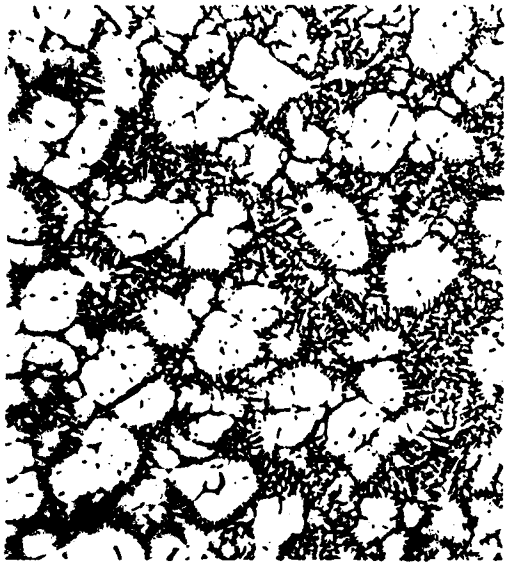
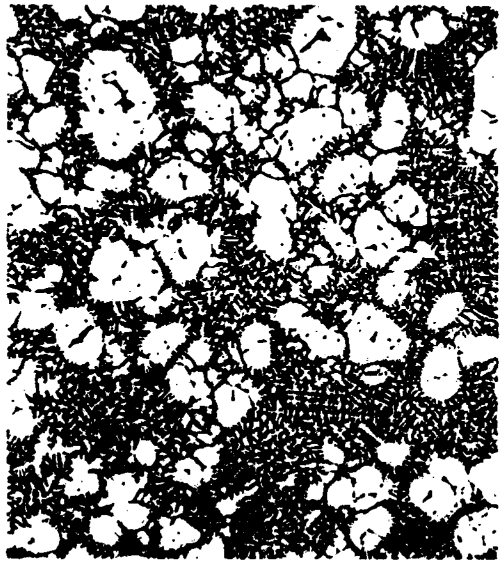


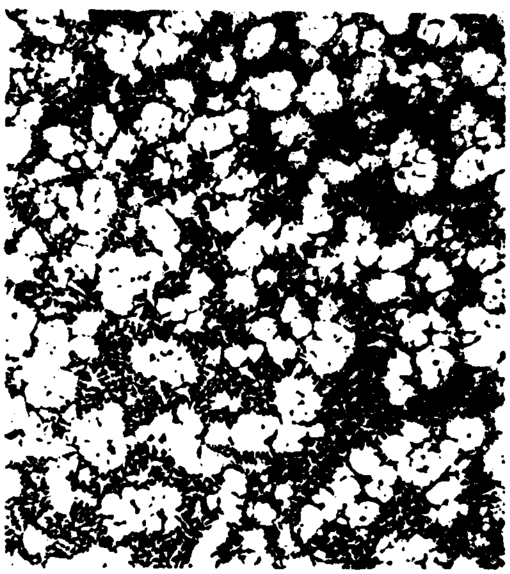
Figure 16. Effect of average shear rate on effective primary solid particle radius in Rheocast 4340. Effect of fractions solid of 0.46, 0.35 and 0.25.



(a)



(b)



(c)

Figure 17. Microstructures of Rheocast AISI 4340 slurries with volume fractions solid of 0.46 and produced with shear rates of (a) 360 sec^{-1}, (b) 540 sec^{-1}, and (c) 720 sec^{-1}. 25.6X.

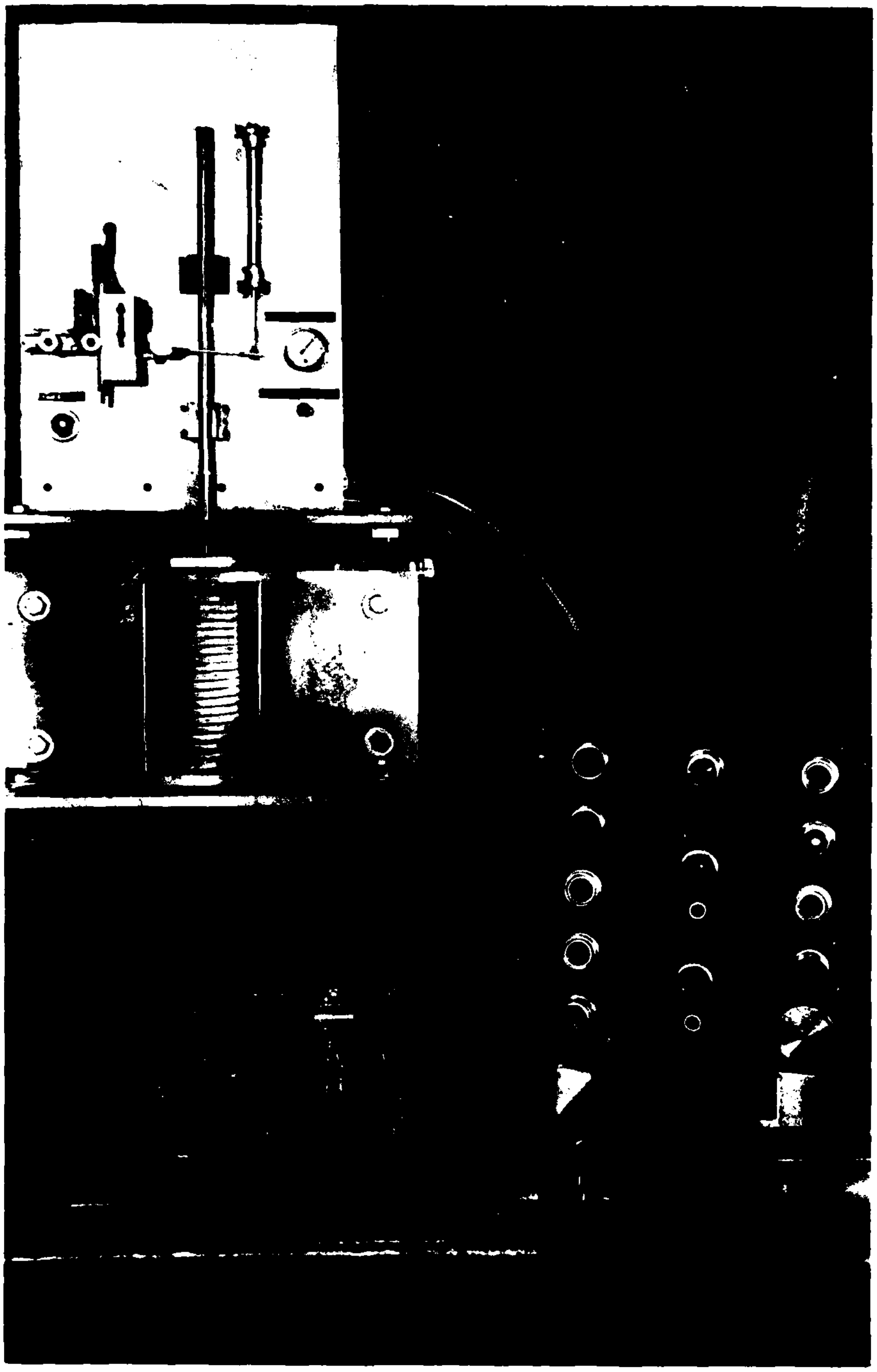


Figure 18. The Thixocast reheat station, including the inductively powered reheat furnace and the Softness Indicator.

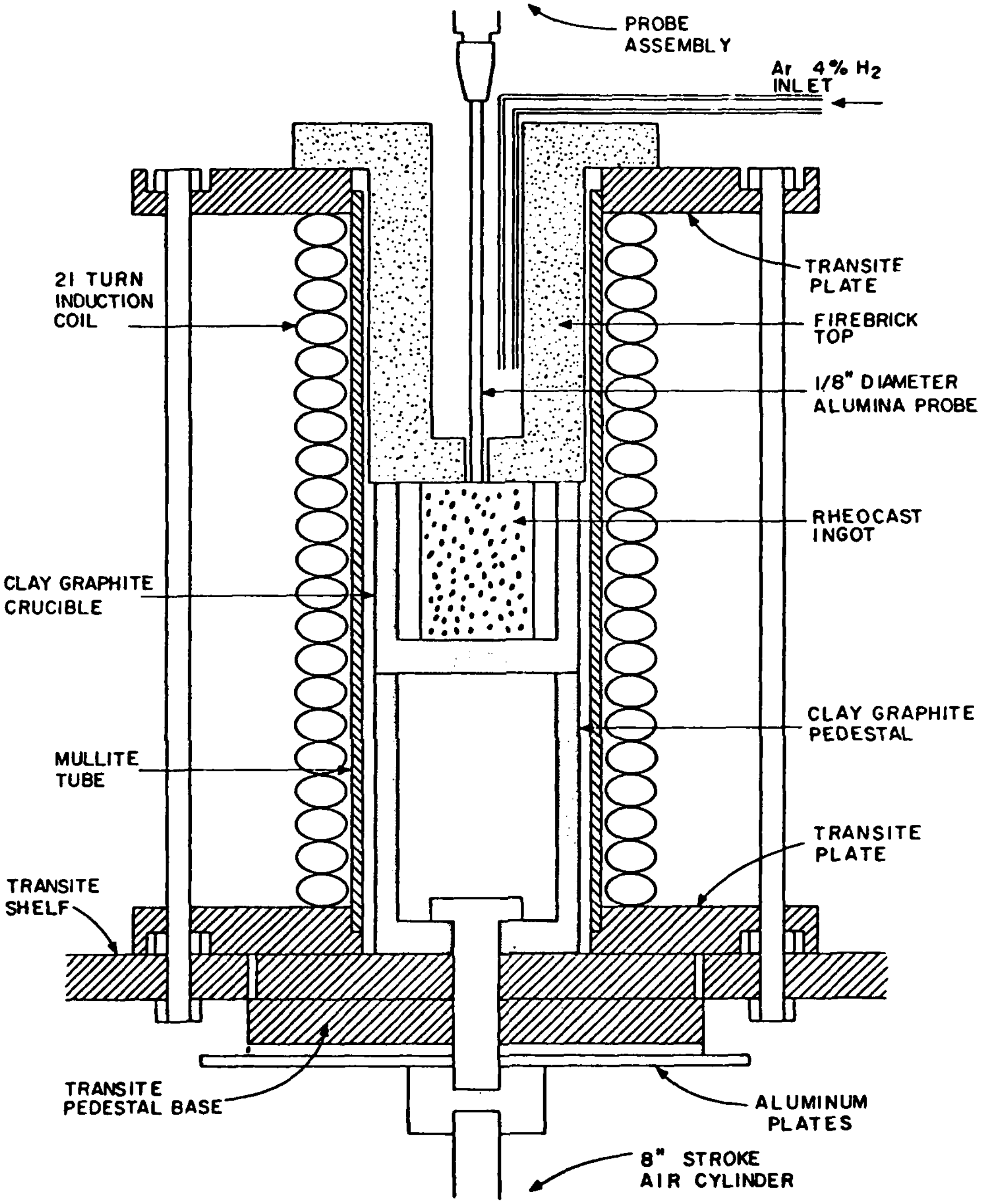


Figure 19. Schematic cross-section of the Thixocast reheat furnace.

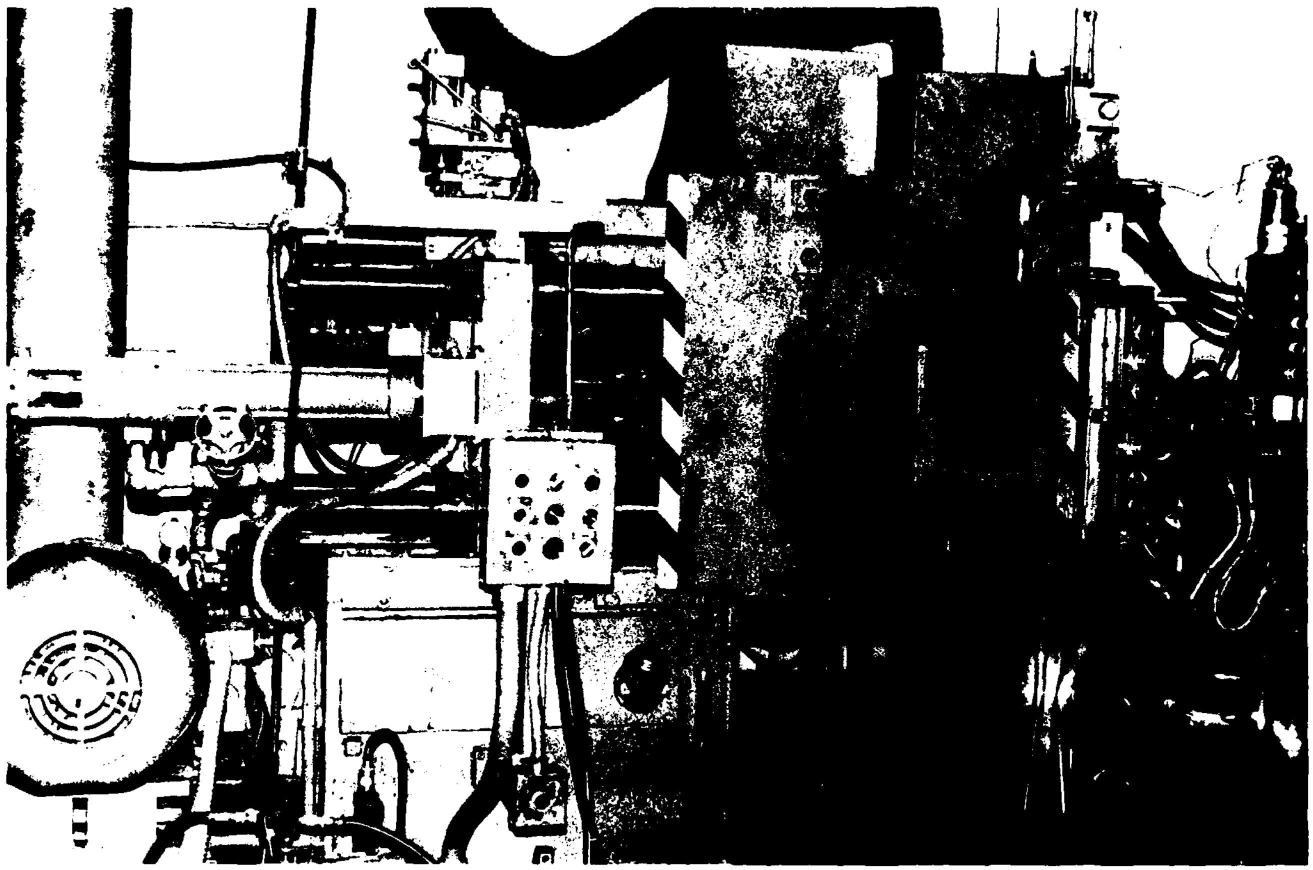


Figure 20. Photograph of the B & T Greenlee 125-ton cold chamber die casting machine.

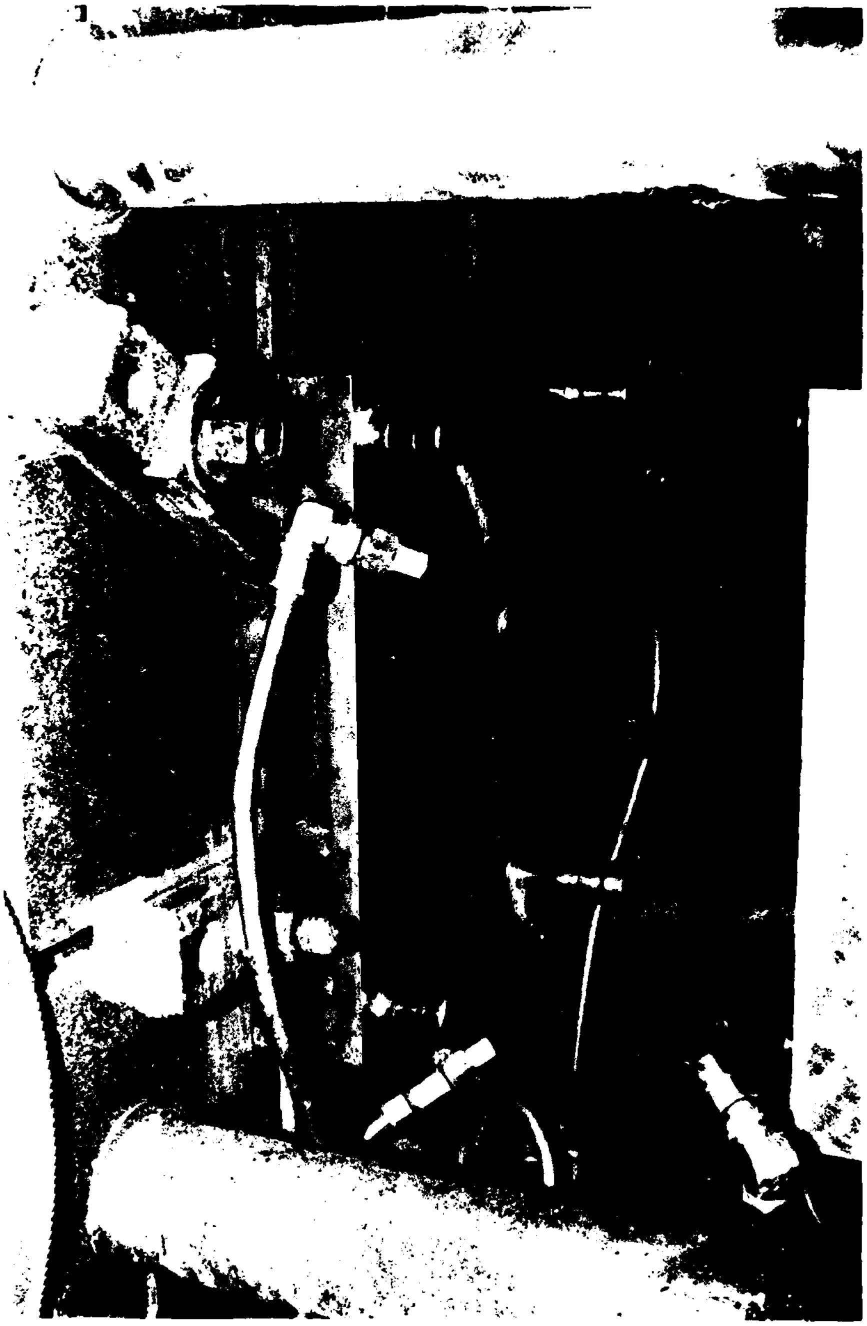


Figure 21. Photograph of the external water spray system for die cooling.

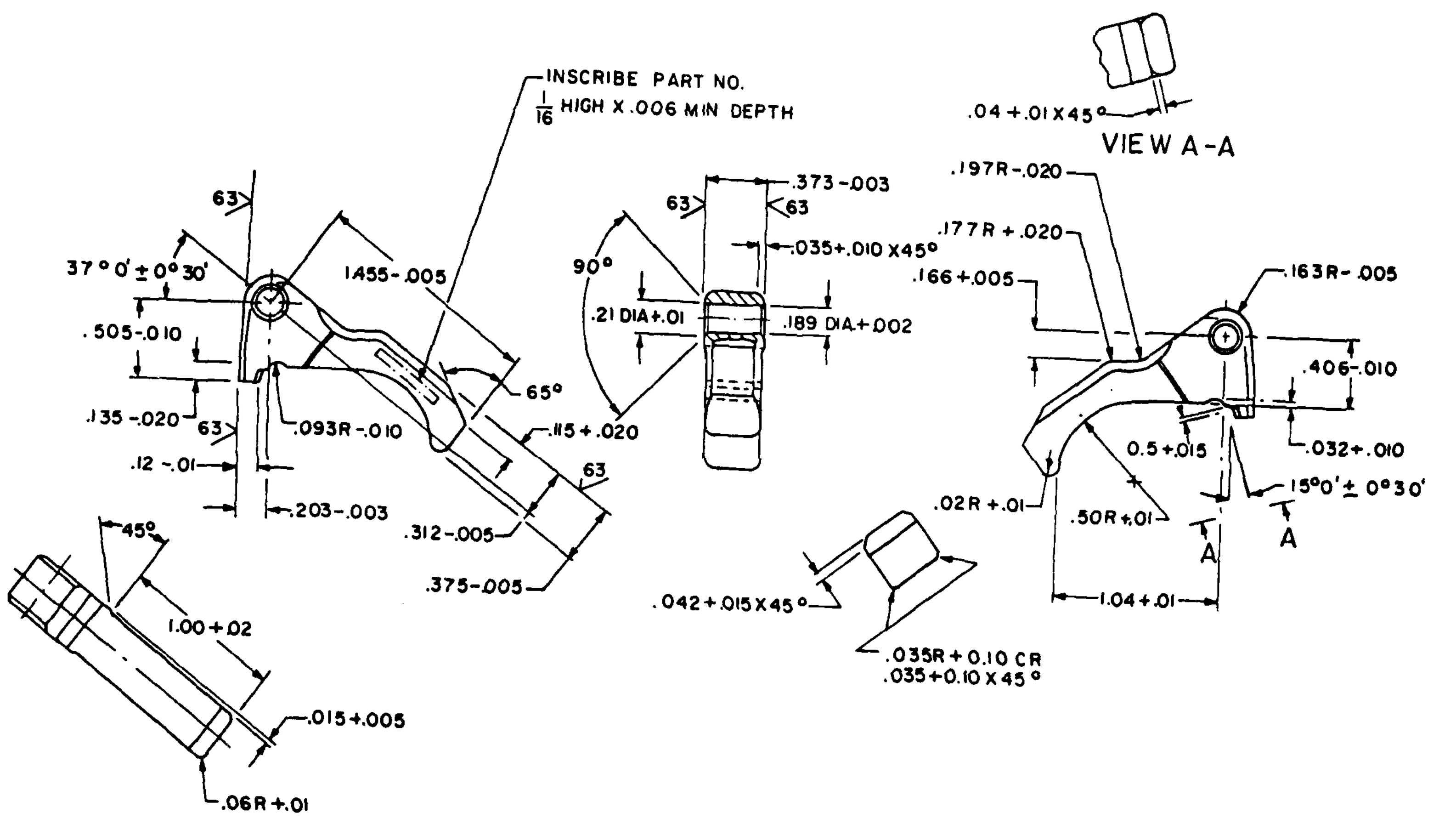


Figure 22. Specifications for the M-85 pawl, cartridge stop. (Supplied by the Department of the Army, Rock Island Arsenal.)

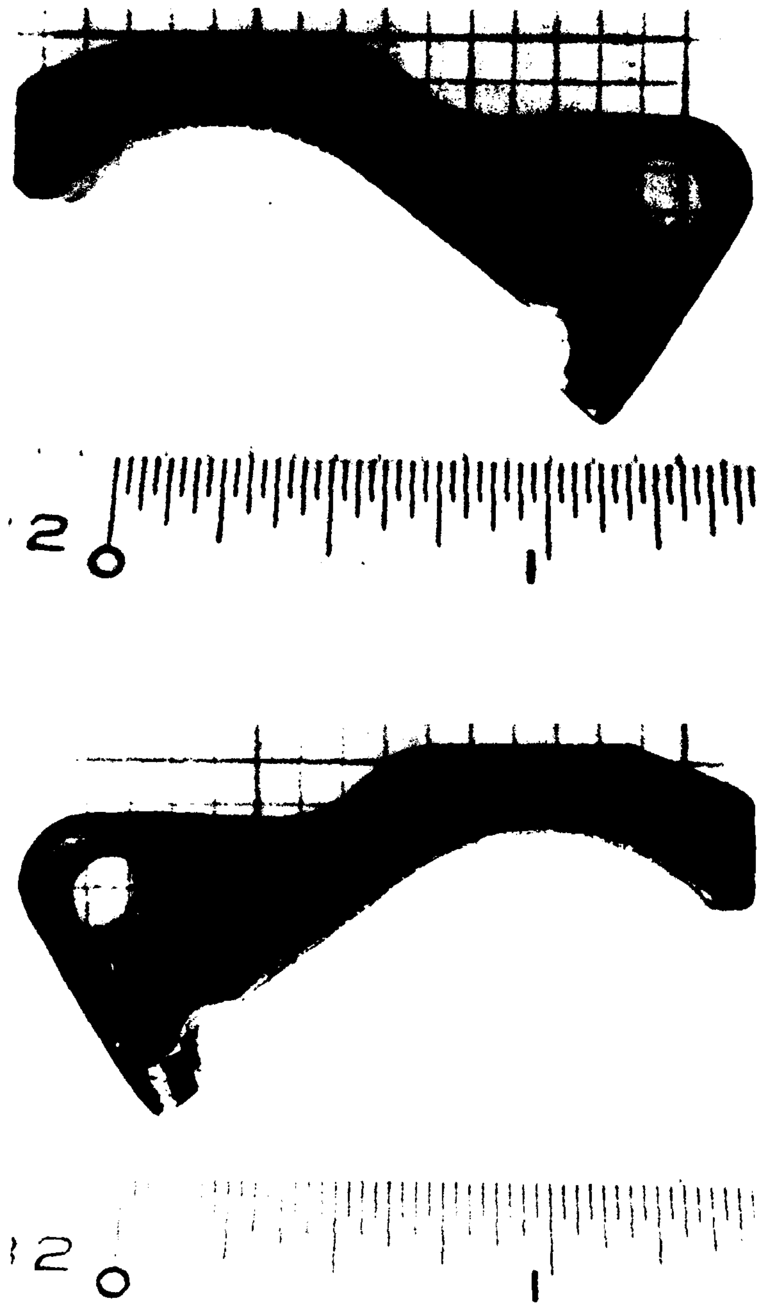


Figure 23. The actual forged and finished M-85 pawl, cartridge stop. (As received by the Department of the Army, Watertown Arsenal.)

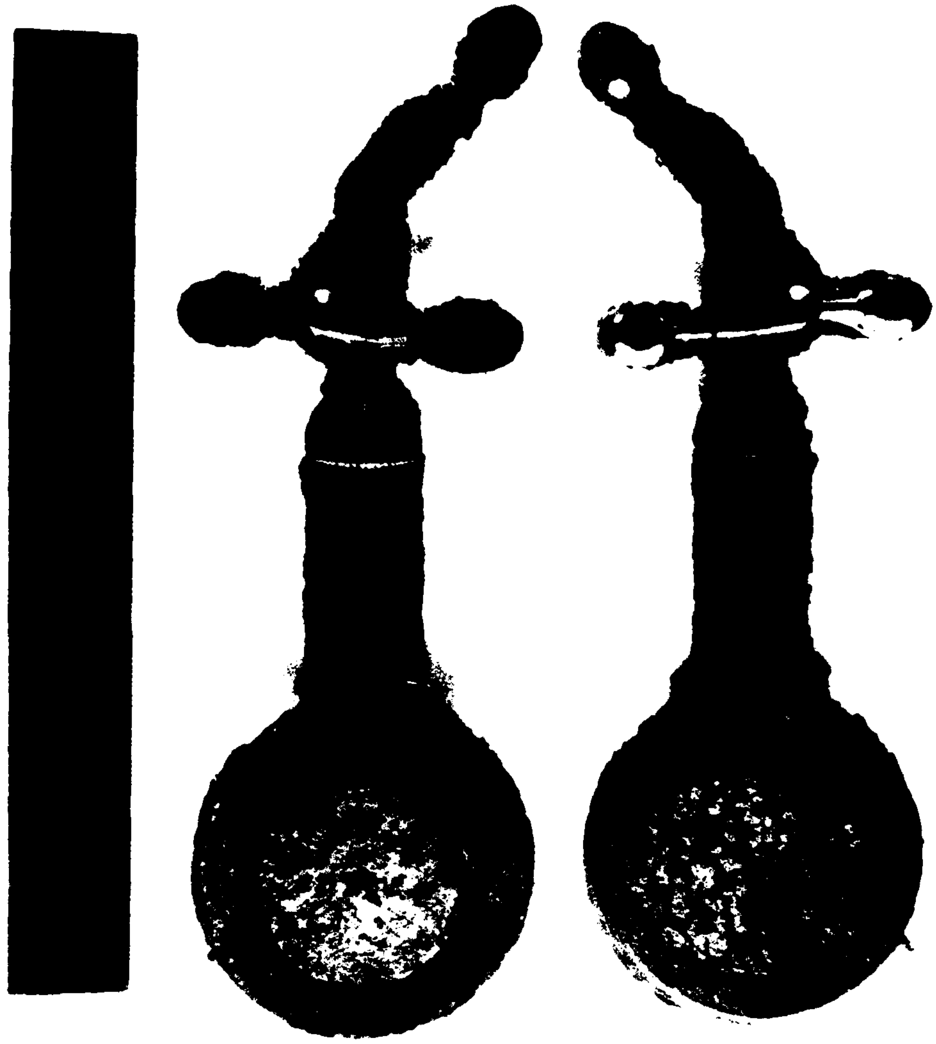


Figure 24. Photograph of the entire M-85 die casting, including overflows, runner and biscuit.

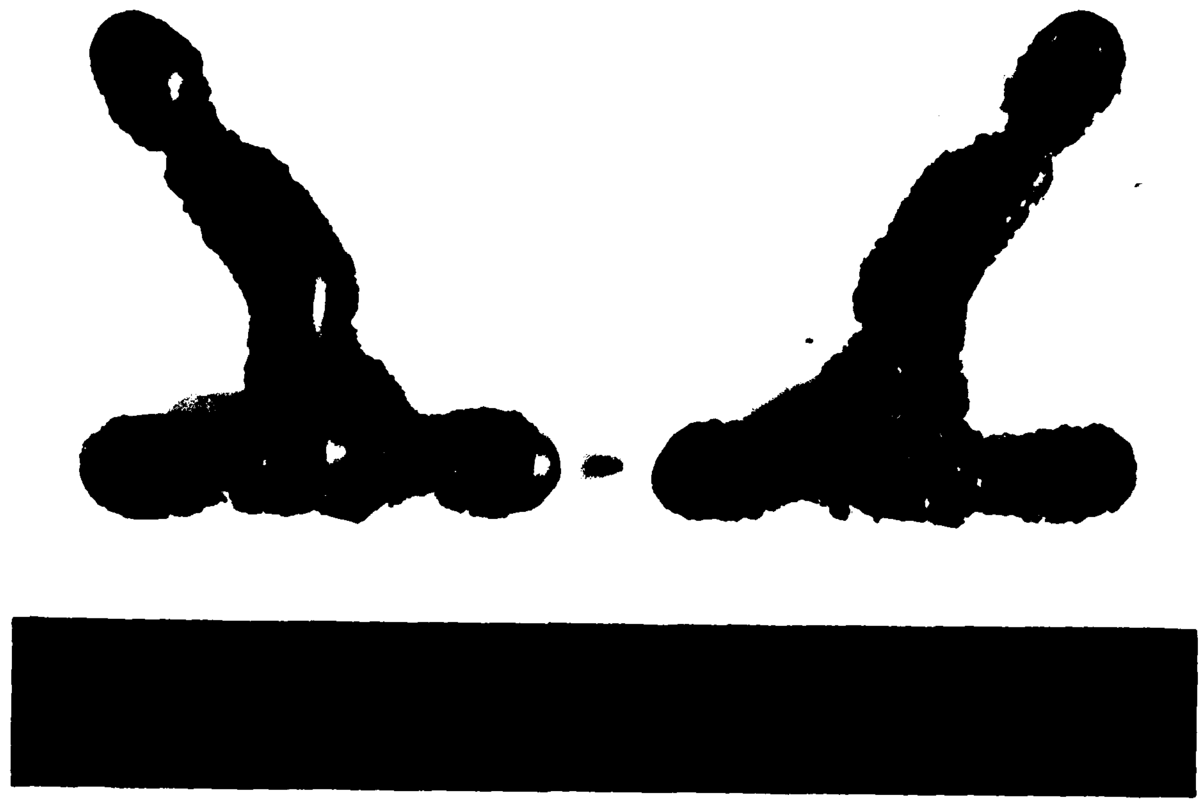


Figure 25. The Thixocast M-85 pawl, cartridge stop, shown in the as-cast condition.

Figure 26. The Thixocast M-85 pawl, cartridge stop, shown in the finished condition.

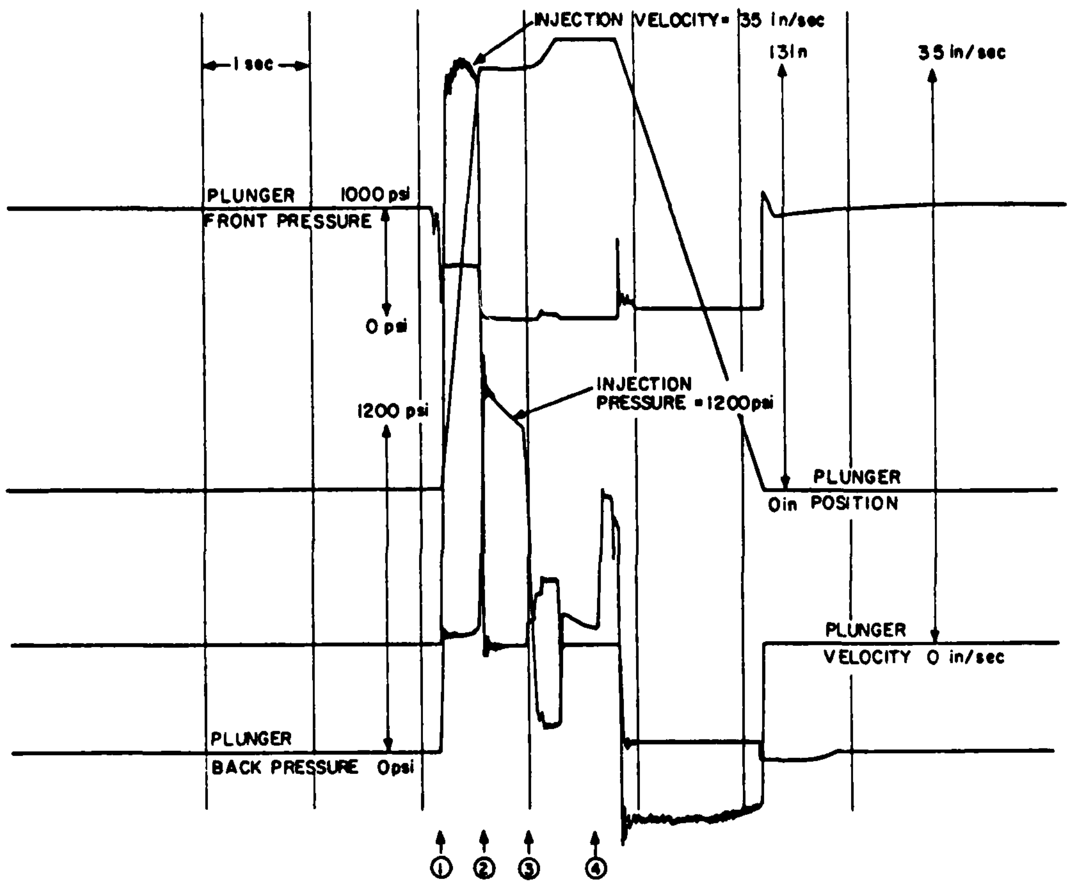
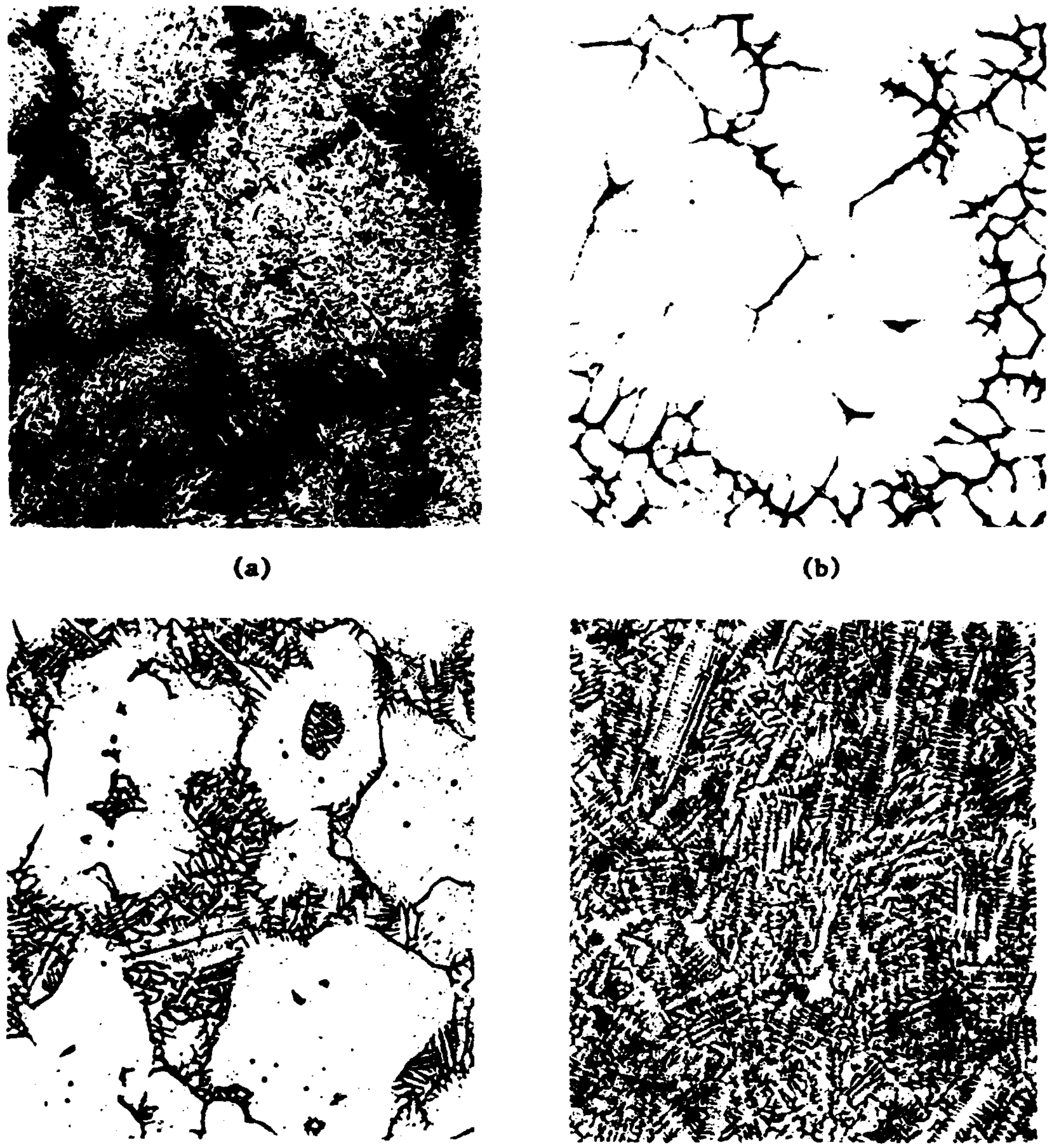


Figure 27. A typical Visicorder trace showing die casting machine conditions during a casting sequence. Injection speed is 35 in/sec and injection hydraulic line pressure is 1200 psi. Numbers indicate chronological order of events during the shot sequence: (1) injection begins, 0 sec., (2) injection complete, full pressurization begins, 0.4 sec., (3) dies begin to open, 0.8 sec., and (4) dies fully opened, water spray cooling begins, 1.4 sec.



(a) (b) (c) (d)

Figure 28. Microstructure of AISI 4340, showing (a) Rheocast ingot structure, (b) Rheocast water-quenched structure, (c) Thixocast structure, and (d) conventional dendritically solidified structure. (128X)

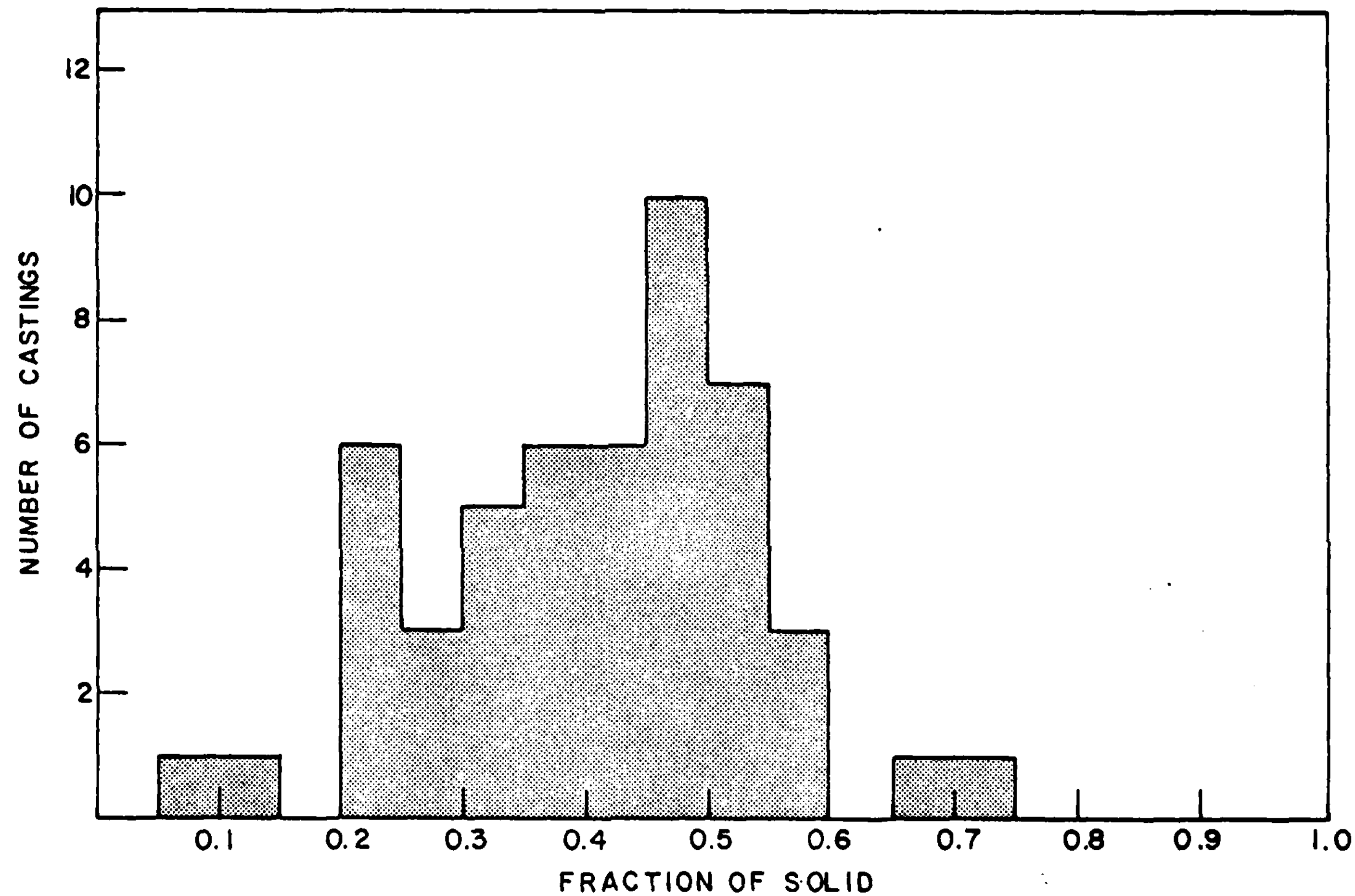


Figure 29. The distribution of fractions of solid measured in 50 randomly selected Thixocastings. The average fraction of solid measured was 0.405.

Figure 30. The radiographic rating scale for Thixocast 4340 steel.

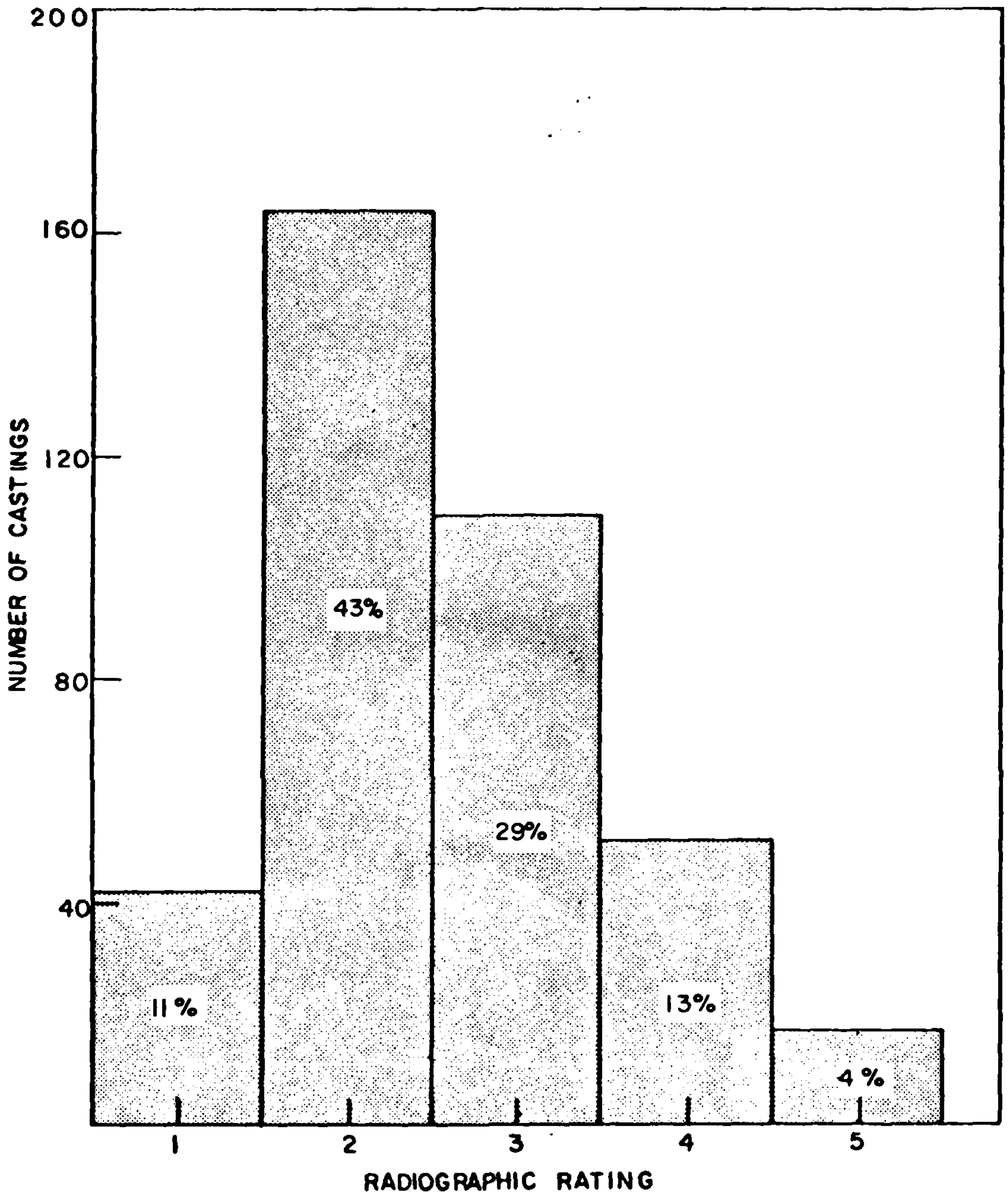


Figure 31. The distribution of radiographic ratings for 383 Thixocastings of 4340 low alloy steel.

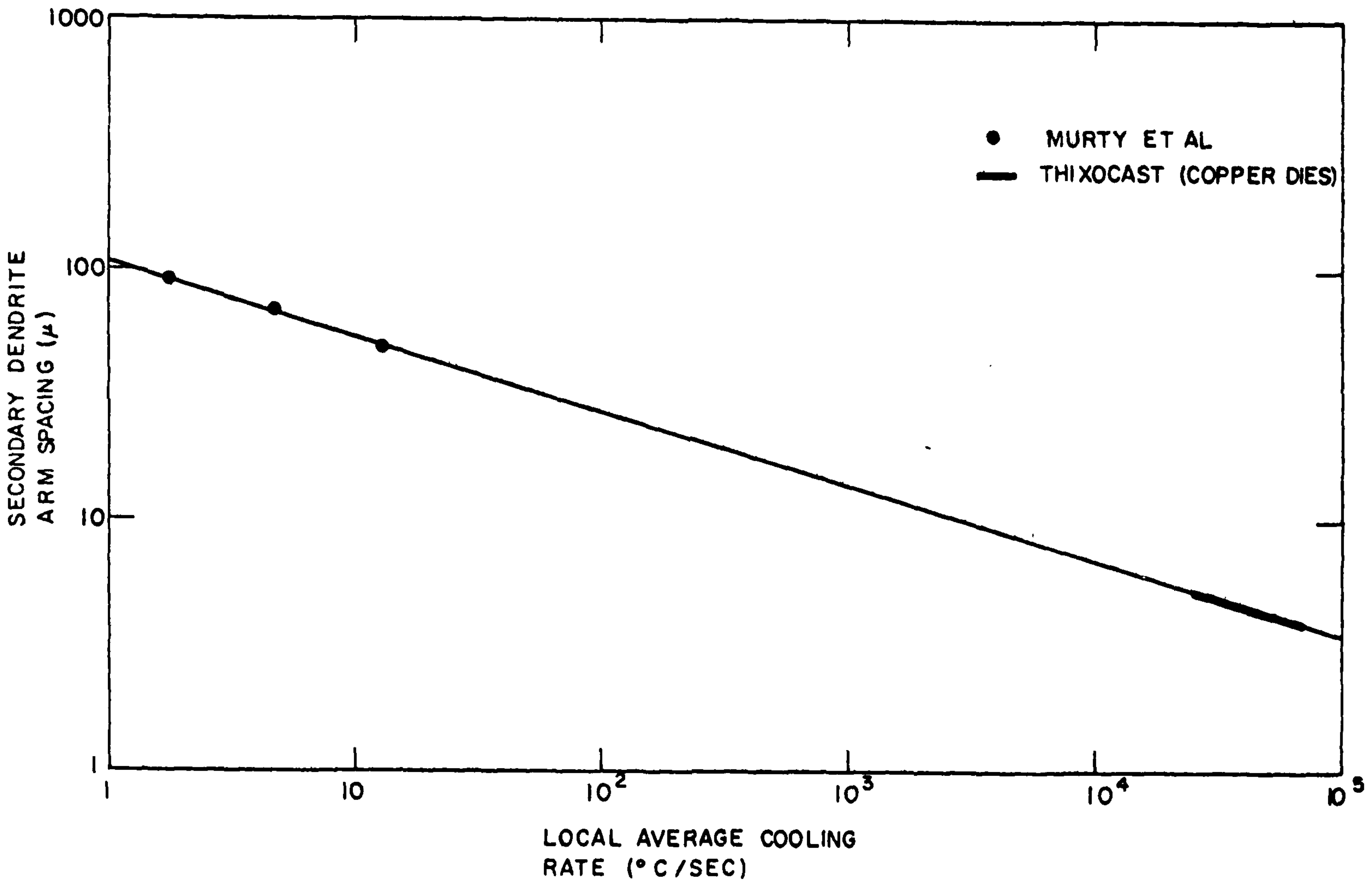


Figure 32. Local average cooling rate versus secondary dendrite arm spacing for AISI 4340 low alloy steel.

Figure 33. The final condition of the plunger tip after exposure to 2,200 shots of Thixocast AISI 4340 low alloy steel.

Figure 34. The final condition of the shot sleeve end after exposure to 2,200 shots of Thixocast AISI 4340 low alloy steel.

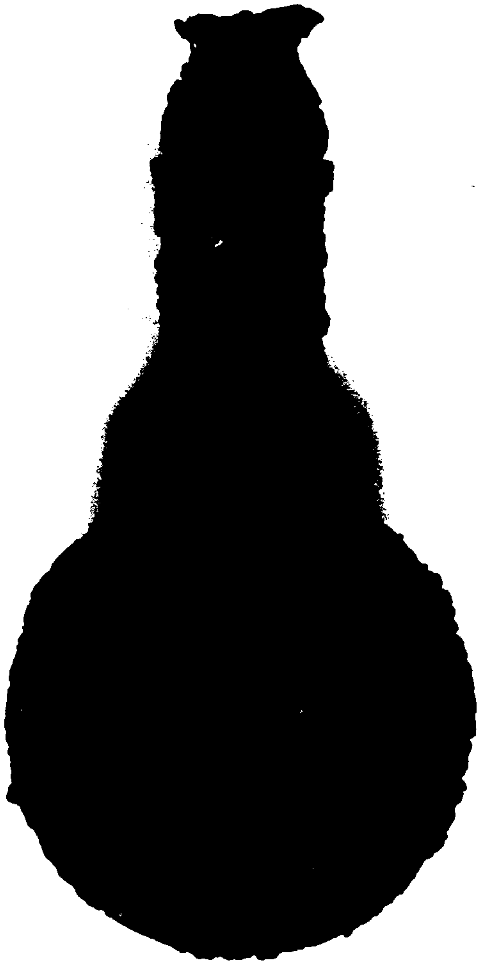
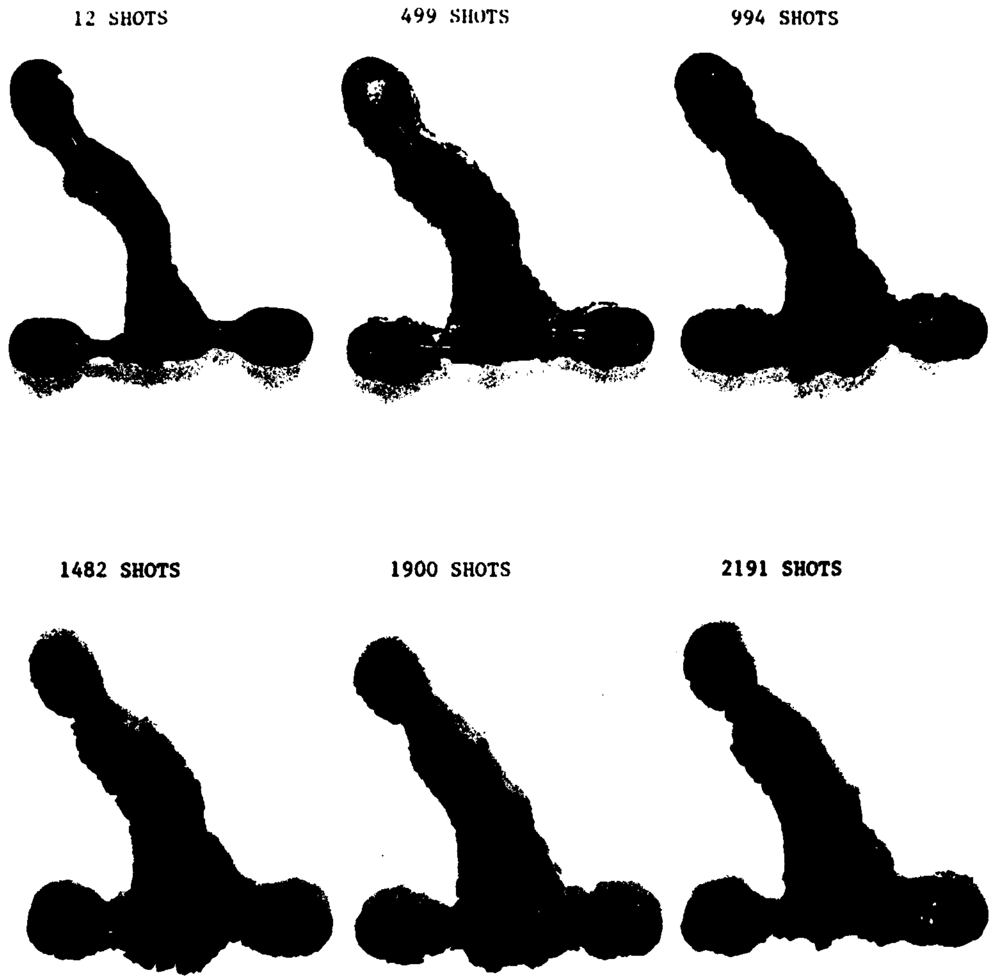


Figure 35. The final condition of runners produced after 2,200 shots of Thixocast AISI 4340 low alloy steel.



THIXOCASTINGS OF THE M-85 PAWL, CARTRIDGE STOP
4340 LOW ALLOY STEEL/ ELBRODUR RS DIES

Figure 36. Sequence of AISI 4340 low alloy steel Thixocastings produced at various intervals in the 2,200 shot die life study for Elbrodur RS copper alloy dies.

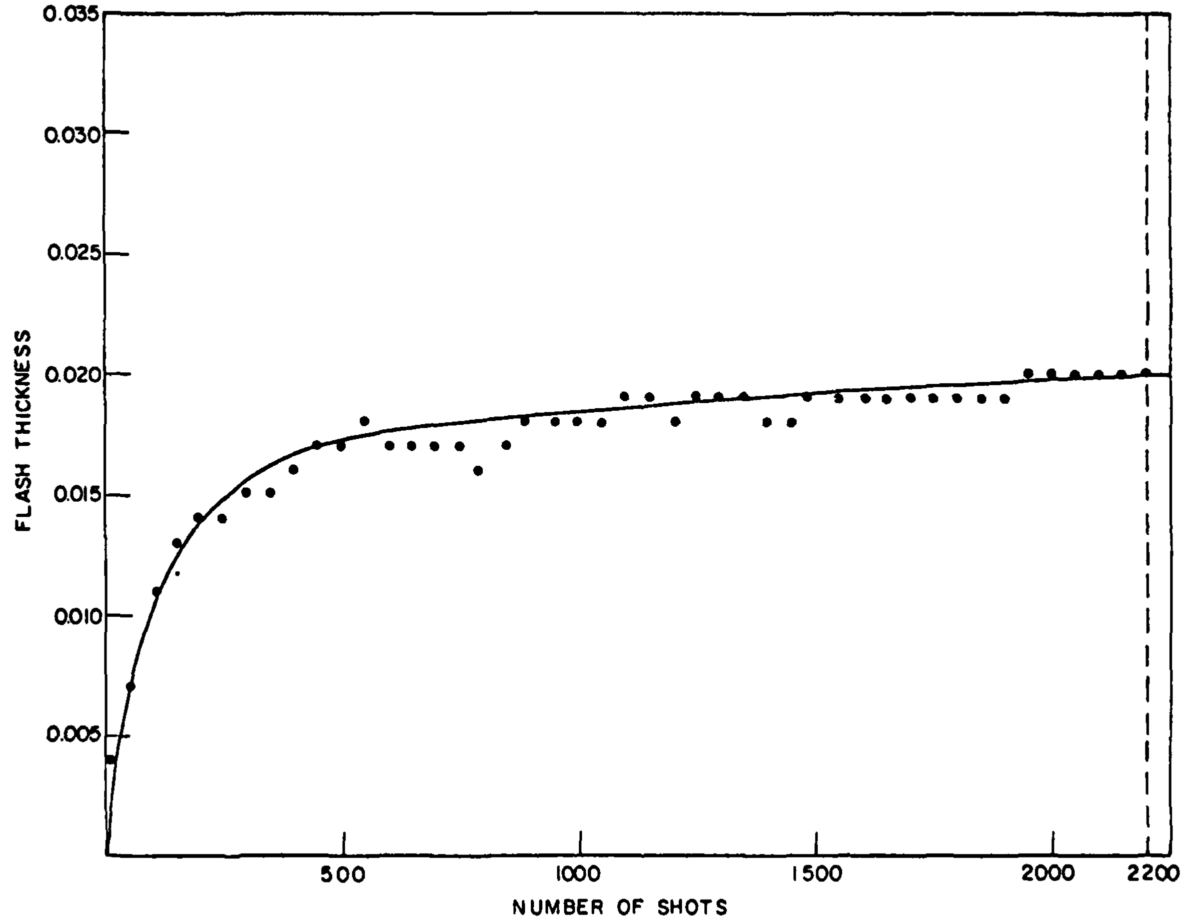


Figure 37. **Flash thickness versus number of shots for AISI 4340 Thixocastings produced in Elbrodur RS copper alloy dies.**

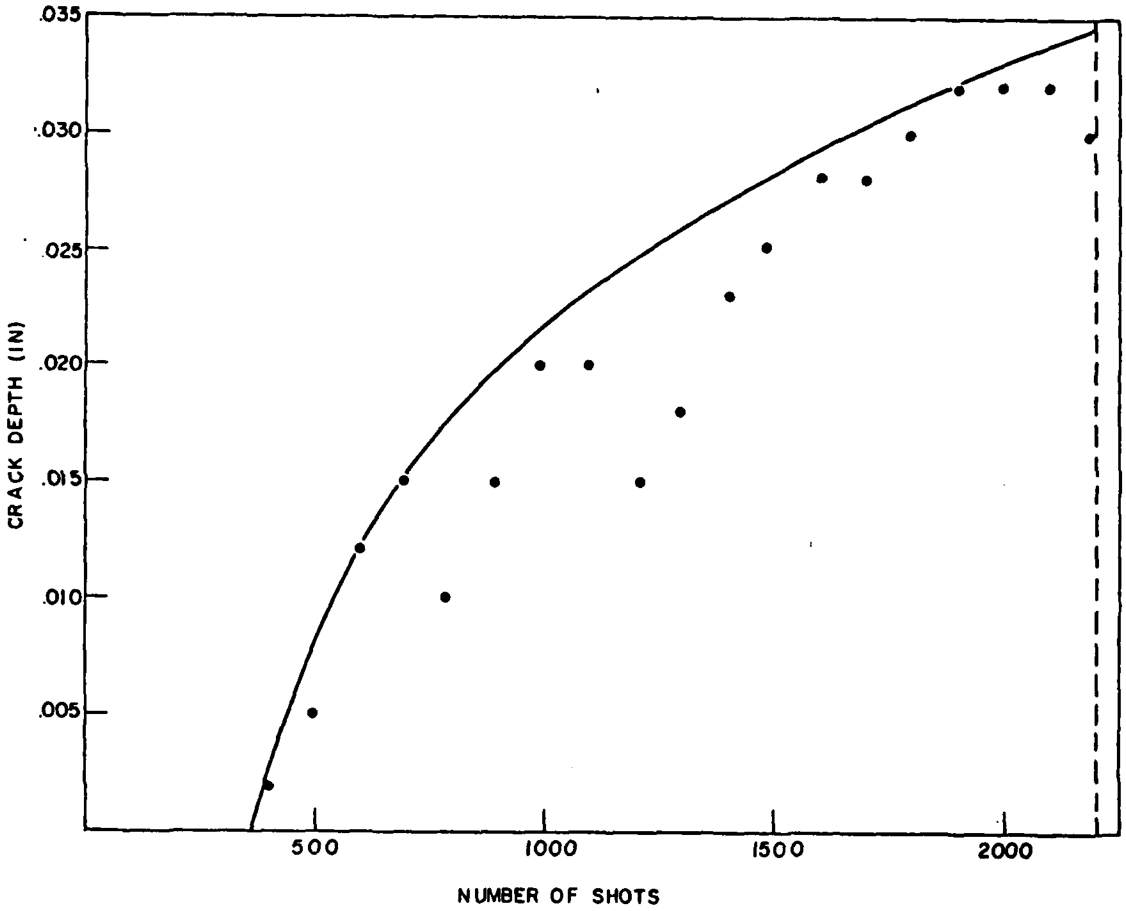


Figure 38. Crack depth versus number of shots for Elbrodur RS copper alloy dies when Thixocasting AISI 4340 low alloy steel. Points represent maximum impression height left on Thixocastings.

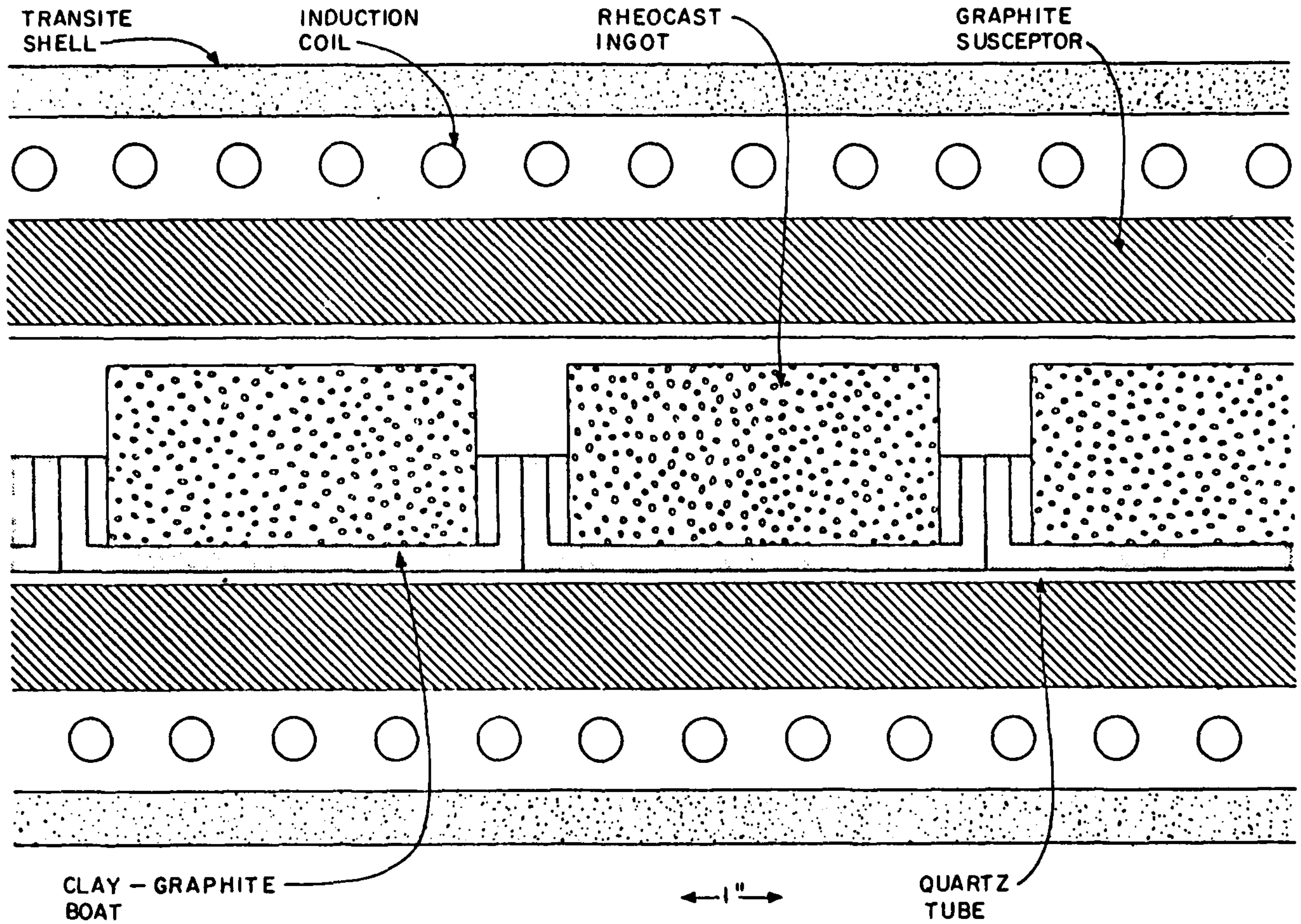


Figure 39. Schematic cross-section of a continuous feed tube reheating furnace for Rheocast 4340 ingot stock.

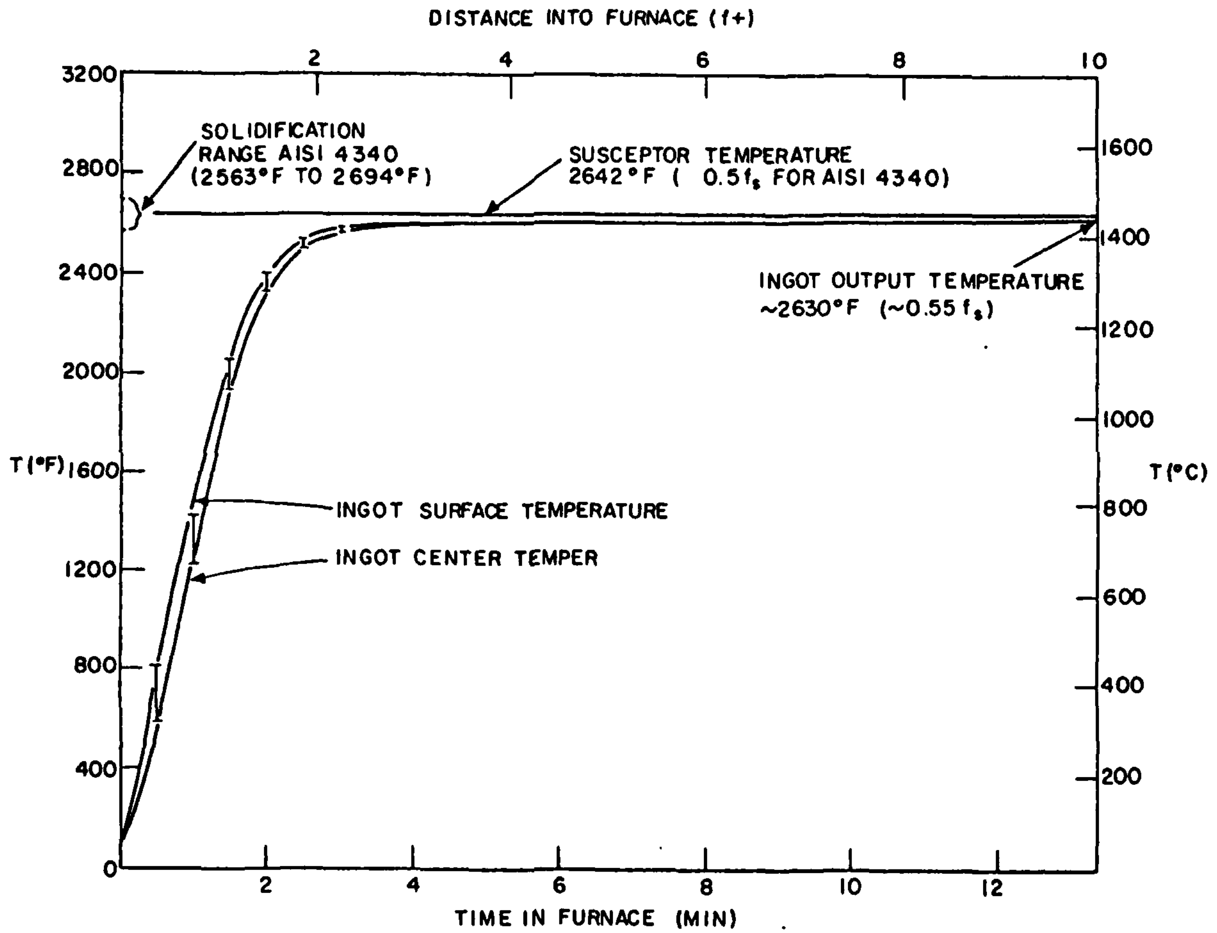


Figure 40. Ingot temperature versus residence time in a continuous feed tube furnace.

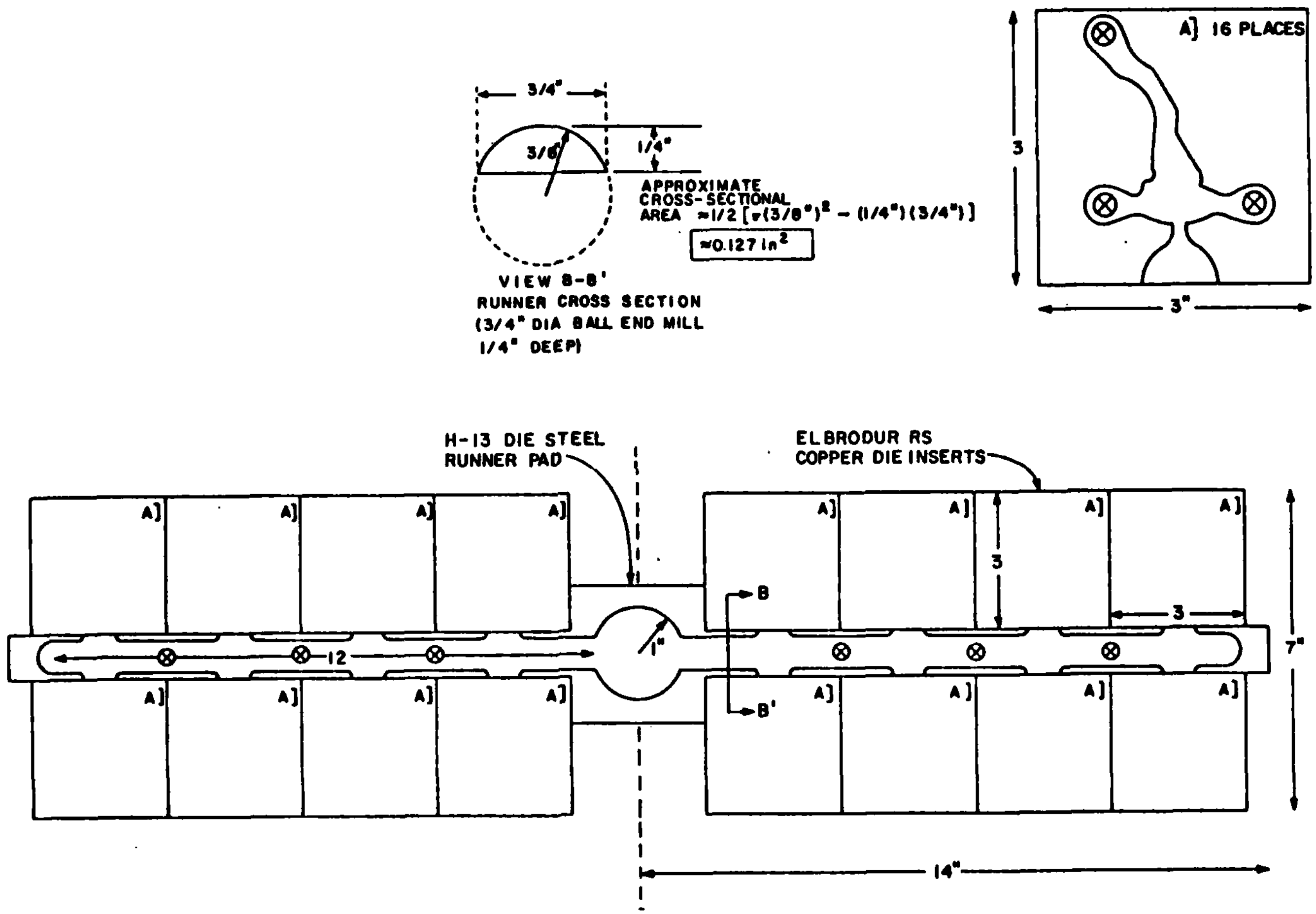


Figure 41. A design for a sixteen cavity die set to Thixocast the M-85 pawl, cartridge stop.

APPENDIX A

M-85 Pawl, Cartridge Stop

Thixocast AISI 4340 Part Data

(note: castings number 19-18 through 24-25 air cooled,

castings number 25-4 through 30-124 vermiculite cooled)

Casting Number	Shot Number	Volume Fraction of Solid	Hardness (R_C)	Volume Percent Porosity	Radiographic Rating
19-18	718		53		3
19-49	749		56		3
19-53	753	0.599	52	3.0	2
19-69	769		53		3
19-80	780	0.494	55	2.9	2
20-1	801	0.369	55	3.3	2
20-18	818		56		2
20-36	836	0.293	50	3.0	3
21-5	864		50		2
21-13	872		48		3
21-16	875	0.408	55	3.4	3
21-20	879	0.417	55	3.1	2
21-30	889	0.401	47	2.9	2
21-32	891		46		2
21-35	894		50		3
21-36	895	0.458	56	4.0	4
21-38	897		53		4

APPENDIX A
(continued)

Casting Number	Shot Number	Volume Fraction of Solid	Hardness (R_C)	Volume Percent Porosity	Radiographic Rating
21-69	921		48		3
21-66	925		51		3
21-70	929	0.502	48	3.7	3
21-72	931		50		2
21-75	934	0.243	56	2.7	3
21-78	937	0.428	48	2.6	2
21-86	945	0.084	48	4.9	4
22-6	965	0.517	55	4.1	3
22-14	973		44		2
22-15	974	0.654	49	2.6	2
22-18	977		50		3
22-20	979	0.131	42	2.0	3
23-9	989		46		3
23-21	1001	0.312	49	2.9	2
23-23	1003		44		2
23-34	1014	0.417	50	2.8	2
24-10	1065		48		3
24-25	1080	0.531	46	2.7	4
25-4	1084		24		2
25-5	1085	0.365	34	2.8	2
25-15	1095	0.480	36	2.7	2
26-7	1104	0.394	28	2.8	2

APPENDIX A
(continued)

Casting Number	Shot Number	Volume Fraction of Solid	Hardness (R_C)	Volume Percent Porosity	Radiographic Rating
26-30	1127		27		3
26-33	1130		18		2
26-41	1138	0.488	24	2.9	2
26-45	1142	0.218	30	2.9	2
26-59	1156	0.566	24	2.1	2
26-61	1158		30		3
26-63	1160	0.492	29	2.5	2
26-71	1168	0.508	19	3.1	2
26-77	1174		22		2
26-79	1176		26		3
26-86	1183	0.520	27	3.3	3
26-98	1195		27		2
26-100	1197	0.356	32	5.6	5
27-15	1215		28		2
27-20	1220	0.712	30	2.7	4
27-28	1228		26		3
27-30	1230	0.470	33	2.2	2
27-31	1231		34		3
27-34	1234		33		2
27-37	1237	0.455	27	4.2	4
27-41	1241		25		3
27-49	1249	0.469	32	2.8	2

APPENDIX A
(continued)

Casting Number	Shot Number	Volume Fraction of Solid	Hardness (R_C)	Volume Percent Porosity	Radiographic Rating
27-59	1259		26		2
27-63	1263	0.533	27	2.4	3
27-67	1267	0.403	22	2.0	2
27-68	1268		26		3
27-77	1277		22		2
27-80	1280	0.579	22	3.0	2
27-89	1289		25		3
27-96	1296		20		3
27-108	1308	0.212	25	4.8	4
27-118	1318		20		3
27-122	1322	0.498	23	3.5	3
28-22	1347		22		4
28-26	1351	0.516	24	2.9	3
28-36	1361	0.212	28	2.4	3
28-38	1363	0.366	23	2.4	2
28-42	1367		19		4
28-52	1377		20		3
28-53	1378		24		3
28-65	1390	0.450	21	4.9	3
28-78	1403	0.365	25	3.1	3
28-85	1410		25		2
28-92	1417		16		3

APPENDIX A
(continued)

Casting Number	Shot Number	Volume Fraction of Solid	Hardness (R_C)	Volume Percent Porosity	Radiographic Rating
29-50	1515	0.305	19	3.9	4
29-58	1523		24		3
26-74	1539		18		3
29-75	1540	0.332	30	5.6	4
29-86	1551		13		4
29-87	1552	0.247	15	3.2	3
29-91	1556		27		3
29-103	1568		27		2
30-49	1649	0.299	19	4.0	4
30-57	1657		18		3
30-58	1658	0.310	19	3.0	3
30-63	1663		21		3
30-81	1681	0.333	20	5.4	4
30-90	1690		23		4
30-93	1693	0.236	32	5.6	4
30-108	1708		15		4
30-124	1724	0.298	25	2.7	3

APPENDIX B

M-85 Pawl, Cartridge Stop

Elbrodur RS Die Insert Wear Data

Casting Number	Shot Number	Flash Thickness (in.)	Heat Check Impression Height (in.)	Casting Thickness (in.)
2-9	12	0.004	0	0.341
2-47	50	0.007		0.342
5-43	107	0.011	0	0.341
6-35	149	0.013		0.342
7-11	200	0.014	0	0.340
7-60	249	0.014		0.341
8-36	300	0.015	0	0.343
10-19	349	0.015		0.342
11-10	400	0.016	0.002	0.343
11-60	450	0.017		0.343
13-14	499	0.017	0.005	0.342
15-15	550	0.018		0.343
17-4	604	0.017	0.012	0.340
17-49	649	0.017		0.343
18-42	692	0.017	0.015	0.341
19-50	750	0.017		0.341
19-90	790	0.016	0.010	0.343
20-49	849	0.017		0.341
21-31	890	0.018	0.015	0.341
21-91	950	0.018		0.341
23-14	994	0.018	0.020	0.342

APPENDIX B
(continued)

Casting Number	Shot Number	Flash Thickness (in.)	Heat Check Impression Height (in.)	Casting Thickness (in.)
23-71	1051	0.018		0.341
26-3	1100	0.019	0.020	0.342
26-53	1150	0.019		0.342
27-5	1205	0.018	0.015	0.343
27-50	1250	0.019		0.341
27-101	1301	0.019	0.018	0.342
28-25	1350	0.019		0.341
28-75	1400	0.018	0.023	0.342
28-124	1449	0.018		0.342
29-17	1482	0.019	0.025	0.342
29-83	1548	0.019		0.341
30-5	1605	0.019	0.028	0.343
30-50	1650	0.019		0.343
30-100	1700	0.019	0.028	0.341
31-3	1753	0.019		0.343
31-48	1798	0.019	0.030	0.341
31-101	1851	0.019		0.343
31-150	1900	0.019	0.032	0.341
32-50	1950	0.020		0.341
32-97	1997	0.020	0.032	0.343
32-149	2049	0.020		0.341
33-46	2096	0.020	0.032	0.342

APPENDIX B
(continued)

Casting Number	Shot Number	Flash Thickness (in.)	Heat Check Impression Height (in.)	Casting Thickness (in.)
33-101	2151	0.020		0.343
33-141	2191	0.020	0.030	0.340

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THIXOCASTING STEEL PARTS
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D/A Project: IL162105AH84, AMCMS Code 612105.H840011
Final Report, April 1, 1977-June 30, 1978

Key Words

Rheocasting
Steel
4340 Steel
Thixocasting

This report describes the Thixocasting process as applied to the die casting of small, AISI 4340 parts. 2,200 shots of semi-solid AISI 4340 were cast in an industrial die casting machine to investigate the feasibility of the Thixocast process for this low alloy steel. The Thixocastings produced demonstrate good quality with radiographic examination showing low porosity levels. The rheological behavior of Rheocast AISI 4340 is qualitatively similar to that of other alloys previously studied. Thus, the viscosity of a Rheocast AISI 4340 slurry increases with increasing fraction solid, and at a given fraction solid, it increases with increasing solidification rate and decreasing shear rate. The effective primary solid particle size increases with increasing fraction solid, and over solidification rates of between 0.50 min^{-1} and 1.00 min^{-1}, the effective primary solid particle size at a given fraction solid decreases with increasing shear rate up to a shear rate of 900 sec^{-1}. Cu-1% Cr-19% Zr die inserts used to Thixocast 4340 low alloy steel has been demonstrated to be far superior to standard tool steel die materials (H-13 and H-21) for ferrous alloy machine casting. Die life has been estimated at 10,000 shots and no shot sleeve warpage was encountered when employing the semi-solid charge material. An economic analysis using a specific small AISI 4340 part has been performed to determine the commercial feasibility of the Thixocast process. Assuming a die life of 10,000 shots between reworkings, a manufacturing cost of 15.38¢ per part is calculated for electro-discharge machining (EDM). With investment casting used to shape die cavity inserts, the manufacturing cost is 9.48¢ per part for a similar die life of 10,000 shots. These costs compare favorably with alternate forming processes. For example, the approximate cost of manufacturing the specified part by investment casting would be 16¢ per part.

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